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DEPARTMENT OF THE INTERIOR
FRANKLIN K. LANE, SECRETARY
BUREAU OF MINES
VAN. H. MANNING, DIRECTOR

MEASURING THE TEMPERATURE OF GASES IN BOILER SETTINGS

BY

HENRY KREISINGER
AND
J. F. BARKLEY

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CONTENTS.

Page.

Introduction 7

  Scope of report 7

Acknowledgment 8

Summary of deductions 9

Sources of error in temperature measurements of gases 9

  Error due to radiation 9

    Explanation of diagrams 10

    Tests with Babcock & Wilcox boiler 11

    Tests with single-pass Heine boiler 11

    Tests with double-pass Heine boiler 13

    Tests with Stirling boiler 20

    Description of thermocouples used to detect radiation error 20

    Reducing the radiation error by screening the instrument 23

    Disadvantage of using exposed couples 24

  Variation of temperature of gases at different points in the same cross section 25

    Experiments with Babcock & Wilcox boiler 25

    Experiments with Stirling boiler 26

    Experiments with single-pass Heine boiler 27

    Experiments with double-pass Heine boiler 28

  Fluctuation of temperature at any one point 28

  Temperature drop of gases in flowing through boilers 30

    Temperature drop through tube of a horizontal tubular boiler 30

    Comparison of the temperature drop of gases as they flow through boilers of different types 32

Discussion of radiation error 33

  Causes of radiation in measuring temperatures of gases in boiler settings 33

  Factors affecting heat exchange 34

    Relation of heat radiating and receiving surfaces of instrument 36

  Experimental data showing relation between size of thermocouple and radiation error 38

    Relation between diameter of couple and indicated temperature 39

    Effect of temperature of gases on radiation error 43

    Effect of conditions of exposure of couple on radiation error 43

  Conception of the gas film next surfaces of solids 45

Measuring the temperature of flue gases 48

  Instruments used 48

  Making a copper-constantan thermocouple 50

    Purchasing the elements 50

    Making the hot junction 50

    Making the body of the couple 51

    Arrangement of the couple, its cold junction, and the indicator 52

Measuring the temperature of flue gases—Continued.

Page.
Manipulation of the potentiometer 54
Adjusting the instrument 54
Reading the temperatures 56
Examples 56
Placing a thermocouple for measuring flue-gas temperatures 57
Usefulness of temperature measurements 60
Calibration of thermocouple 61
Calibration by known melting points of metals and boiling point of water 62
Preparing the molten bath 62
Precautions in making readings 62
Plotting the calibration curve 64
Calibration by comparison with high-reading mercury thermometer 64
Publications on the utilization of coal and lignite 67
Publications available for free distribution 67
Publications that may be obtained through the Superintendent of Documents 68

ILLUSTRATIONS.

Page.

FIGURE 1. Curves showing temperatures of gases flowing through a Babcock & Wilcox boiler 12
2. Cross section of Babcock & Wilcox boiler, fired with natural gas 13
3. Curves showing temperatures of gases flowing through a single-pass Heine boiler 14
4. Single-pass Heine boiler, equipped with Jones underfeed stoker 15
5. Curves showing temperatures of gases flowing through a double-pass Heine boiler 16
6. Cross section of double-pass Heine boiler, connected to experimental hand-fired furnace 17
7. Curves showing temperature of gases flowing through a Parker boiler 18
8. Cross section of Parker boiler 19
9. Curves showing temperatures of gases flowing through a Stirling boiler 22
10. Cross section of Stirling boiler, fired with natural gas 23
11. Construction of twin couples used in temperature measurements shown in figures 1, 3, 5, 7, and 9 24
12. Curves showing variations of temperature at different points of the same cross section in a Babcock & Wilcox boiler fired with natural gas 26
13. Curves showing variations of temperature at different points of the same cross section in a Stirling boiler fired with natural gas 27
14. Curves showing variations of temperature at different points in a standard single-pass Heine boiler equipped with a Jones underfeed stoker 28
15. Curves showing variations of temperature at different points in a double-pass Heine boiler receiving hot gases from a hand-fired experimental furnace 29
16. Curves showing fluctuations of temperature at points A and C in the Babcock & Wilcox boiler shown in figure 2 29
17. Curves showing variations in temperature of gases flowing through a horizontal tubular boiler 31
18. Diagram showing that the surface radiating heat decreases faster than the surface receiving heat by convection, when the diameter of the instrument decreases 38
19. Curves showing temperatures indicated by couples of different sizes when placed in same position in a boiler setting 40
20. Curves showing relation between diameter of couple and temperature indicated by couple, when measuring temperature of hot gases surrounded by cooler surfaces 41

Page.
21. Curves showing effect of temperature of gases on radiation error 44
22. Diagram showing the relative velocity of infinitesimal layers in a film of gas next to a solid surface 45
23. Diagram showing variation in velocity of air current across diameter of an 8-inch pipe as actually measured with a small Pitot tube 46
24. Diagram showing variations in temperature of gases across a boiler tube $2\frac{3}{4}$ inches in internal diameter 47
25. Diagram showing construction of body of copper-constantan couple for measuring flue-gas temperature 52
26. Diagram showing arrangement of thermocouple, its cold junction, and the indicating instrument, when measuring the temperature of flue gases 53
27. Top view of a portable potentiometer 55
28. Curve showing relation between millivolts and temperature for a copper-constantan couple 57
29. Setting of a Stirling boiler at plant of U. S. Reclamation Service, Williston, N. Dak. 59
30. Arrangement of apparatus for calibrating thermocouple by known melting points of metals 63
31. Curves showing method of obtaining the melting point of a metal from a series of readings 65

MEASURING THE TEMPERATURE OF GASES IN BOILER SETTINGS.

By **Henry Kreisinger** and **J. F. Barkley**.

INTRODUCTION.

This book is one of a series of publications being issued by the Bureau of Mines for the purpose of disseminating information in regard to the methods by which the fuels in this country may be used most efficiently. A knowledge of the temperature of the gases in boiler settings and in other commercial apparatus using heat tends to develop improved designs of apparatus and better methods of operation, thus reducing waste of fuel. The following pages present, for the benefit of those designing, operating, and testing such apparatus, information as to the accuracy of temperature measurements made under certain conditions and the corrections that can be safely applied.

SCOPE OF REPORT.

This bulletin, which may be considered a companion to Technical Paper 80[a] and to Bulletin 97[b] is, like those two publications, intended primarily for boiler-room operators or testing engineers. Also, it may be found helpful to men in other industrial establishments where measurements of the temperatures of gases are desirable. The bulletin presents the results of a series of measurements of the temperatures of gases in the most common types of boilers, discusses the errors occurring in the usual methods of measurement, and gives directions for making and using inexpensive thermocouples to determine flue-gas temperatures. In these directions only such tools are recommended as are available in an ordinary boiler plant.

The reader should remember that the degree of accuracy of gas-temperature measurements depends more on the judgment of the user than on the correct calibration of the temperature-measuring instrument. Often an instrument so well calibrated that its readings are correct to within a degree is carelessly placed in a gas passage and its readings reported to three or four figures without due consideration being given the multiplicity of errors that are sure to occur. Because the instrument is known to be calibrated accurately the readings are assumed to represent the correct temperatures of the gases. It is not the intention of the writers to belittle the value of accurate calibration, but to emphasize the need of using extreme care in placing the instrument in the gas passage, and of exercising judgment in interpreting the readings.

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[a] Kreisinger, Henry, and Ovitz, F. K., Sampling and analysis of flue gases: Bull. 97, Bureau of Mines, 1915, 83 pp.

[b] Kreisinger, Henry, and Ovitz, F. K., Sampling and analysis of flue gases: Bull. 97, Bureau of Mines, 1915, 70 pp.

The material in this bulletin is presented in three parts. The first part contains the results of a series of measurements of the temperatures of the gases within boiler settings of five common types of boilers. The temperatures were measured with thermocouples of different sizes so as to bring out the character and the magnitude of the errors that are bound to occur in such measurements. The data are graphically presented in the form of curves or diagrams, accompanied by a description of the apparatus and the methods of making the tests, with a general discussion of the sources of error. This part will be of interest to the boiler designer and the operator.

The second part, which explains why the readings obtained with small-size couples are nearer to the true temperature of the gases than those obtained with large couples or other large instruments, shows the relation between the magnitude of the radiation error and the size of the couple. This relation was obtained experimentally and was also deduced algebraically from known laws of heat transmission. Hence the second part of the report should interest those who wish to ascertain the causes of the radiation error, which is the largest and most serious error in measuring gas temperatures.

The third part contains a discussion of the various instruments used, and also directions on making a copper-constantan thermocouple and using it for measuring the temperatures of flue gases. This part of the report is of interest to anyone who may wish to measure the temperature of gases up to 1,000° F.

ACKNOWLEDGMENT.

The authors wish to express their appreciation to W. Trinks, professor of mechanical engineering of the Carnegie Technical Schools, and to J. P. Weidlein, superintendent of the power plant of the schools, for their courtesy in making arrangements for the authors to use the boilers of the institution for obtaining much of the data presented in this bulletin. Special credit is due E. M. Muncey, physical laboratory aid, of the Bureau of Mines, for assistance in preparing the apparatus and collecting the data.

SUMMARY OF DEDUCTIONS.

When the temperature of hot gases surrounded by colder surfaces is measured with an ordinary thermometer or a protected thermocouple, the temperature indicated by the measuring instrument is always too low. Heat is constantly radiated from the measuring instrument to the colder surfaces, thus keeping the temperature of the instrument lower than that of the hot gases. The error may amount to several hundred degrees Fahrenheit.

The greater the difference is between the temperature of the gases and that of the surrounding surfaces, the greater is the error. Also, the error is larger with instruments having the exposed parts large than with those having such parts small. Thus, for an example, a couple having the hot junction inclosed in a protecting tube will invariably read considerably lower than an unprotected couple. The smaller the wires at the hot junction of the couple the nearer is the temperature indicated by the couple to that of the gases.

The true temperature of the gases would be indicated by a couple having the hot junction made of wire of zero diameter. The true temperature can be obtained approximately by using three or more couples of various sizes and determining from these readings by extrapolation the theoretical indication of a couple of zero diameter.

Ordinary methods of measurement show flue-gas temperatures that are on the average about 20° F. too low.

Copper-constantan can be used advantageously for measuring the temperature of flue gases.

SOURCES OF ERROR IN TEMPERATURE MEASUREMENTS OF GASES.

Accurate measurement of the temperatures of the gases as they pass through a boiler setting is extremely difficult, especially where the temperature of the gases differs greatly from that of the surrounding surfaces. Under such conditions the results obtained by ordinary methods of measurement are seldom correct within less than 10 per cent, and are frequently off 25 per cent. The errors in the measurements are due chiefly to three causes, as follows:

1. Radiation from the instruments with which the temperatures are measured. This error usually makes the observations too low.
2. Variation of the temperature of the gases at different points in a cross section of the path of the gases. This error may make the readings too low or too high; more often, too low.
3. Fluctuation of temperature at any one point may cause the reading to be too low or too high.

ERROR DUE TO RADIATION.

Of these three sources of error in measuring the temperatures of the gases inside of a boiler setting, radiation is apt to be the most important; the error from this cause may amount to 25 per cent of the actual temperature, the magnitude depending largely on the size of the measuring instrument. When the part of the instrument immersed in the gases is large the error is large. Exposed thermocouples made of very fine wires give results much closer to the actual temperature of the gases than thermocouples made of large wires, or the metal-protected high-temperature mercury thermometers. This fact is shown in figures 1, 3, 5, 7, and 9, each of which gives two series of temperature measurements in five types of boilers. One series of these measurements was taken with thermocouples made of wires 0.008 inch in diameter and the other series with couples about 0.5 inch in diameter. The two couples were fastened together, the hot junctions being about 1½ inches apart. Several of such twin couples were placed at different points along the path of the gases as they pass through the boiler. The position of the couples in the different types of boilers is shown in figures 2, 4, 6, 8, and 10. All these couples were read in rapid succession by means of a multiple switch.

EXPLANATION OF DIAGRAMS.

In figures 1, 3, 5, 7, and 9 the abscissas show the approximate length of the path of the gases measured from the point at which the first twin thermocouple was placed; the ordinates show the temperatures and also the approximate velocity of the gases in the boiler settings. Each of the figures contains two groups or sets of curves, the lower one giving data for high initial temperatures and the upper one for low initial temperatures. The upper solid curve is drawn through points representing the temperature readings obtained with the small couple, and the lower heavy curve through points representing the readings obtained with the large couple. The dotted curve above the two solid curves gives the approximate true temperature of the gases, computed on the basis of the experimental data given on page 39. The dashed curve gives the approximate velocity of the gases as calculated from the gas analyses and the composition and amount of fuel used.

In all of the figures the temperature curves show that the small couple consistently indicated temperatures considerably higher than the large couple. The small couple itself read a few per cent too low. The difference between the readings of the two couples was greater when the couples were entirely surrounded by the boiler tubes than when they were partly exposed to the hot brick walls of the setting. Thus in the Babcock & Wilcox boiler the couples in position *B* (see figs. 1 and 2), where they were completely surrounded by the boiler tubes, gave readings much farther apart than the couples in position *A*, where they were partly exposed to the brick walls, which were hotter than the boiler tubes.

TESTS WITH BABCOCK & WILCOX BOILER.

Figure 1 shows the results of temperature measurements of the gases in a Babcock & Wilcox boiler installed at the Carnegie Technical Schools, Pitsburgh, Pa. The boiler was fired with natural gas. A cross section of the boiler, showing the position of the thermocouples and the path of the gases, is given in figure 2.

In figure 2 the positions of the thermocouples are indicated by the small circles designated *A* to *G*. The hot junctions of the thermocouples were within 6 inches of a point midway between the two side walls. The principal dimensions of the boiler are given below:

Dimensions of Babcock & Wilcox boiler used in tests.

Total number of tubes	168
Number of vertical rows	14
Number of horizontal rows	12
Diameter of tubes, inches	4
Length of tubes, feet	18
Heating surface of tubes, square feet	3, 160
Number of steam drums	2
Length of steam drums, feet	20
Diameter of steam drums, inches	42
Approximate effective heating surface of steam drums, square feet	230
Number of coils in superheater	56
Length of coils in superheater, feet	14
Diameter of pipe in superheater, inches	2

TESTS WITH SINGLE-PASS HEINE BOILER.

The results of experiments with a single-pass Heine boiler in the power plant of the experiment station of the Bureau of Mines at Pittsburgh, Pa., are shown in figure 3. This boiler was equipped with a Jones underfeed stoker. A cross section of the boiler is shown in figure 4. The positions of the thermocouples are indicated by the small circles *A* to *D*. The thermocouples *B* and *C* were inserted through stay-bolt holes within 6 inches of a point midway between the two side walls. The principal dimensions of the boiler are given in the following table:

Dimensions of single-pass Heine boiler used in tests.

Total number of tubes		116
Number of horizontal rows		11
Diameter of tubes	feet	3. 5
Length of tubes	do	18

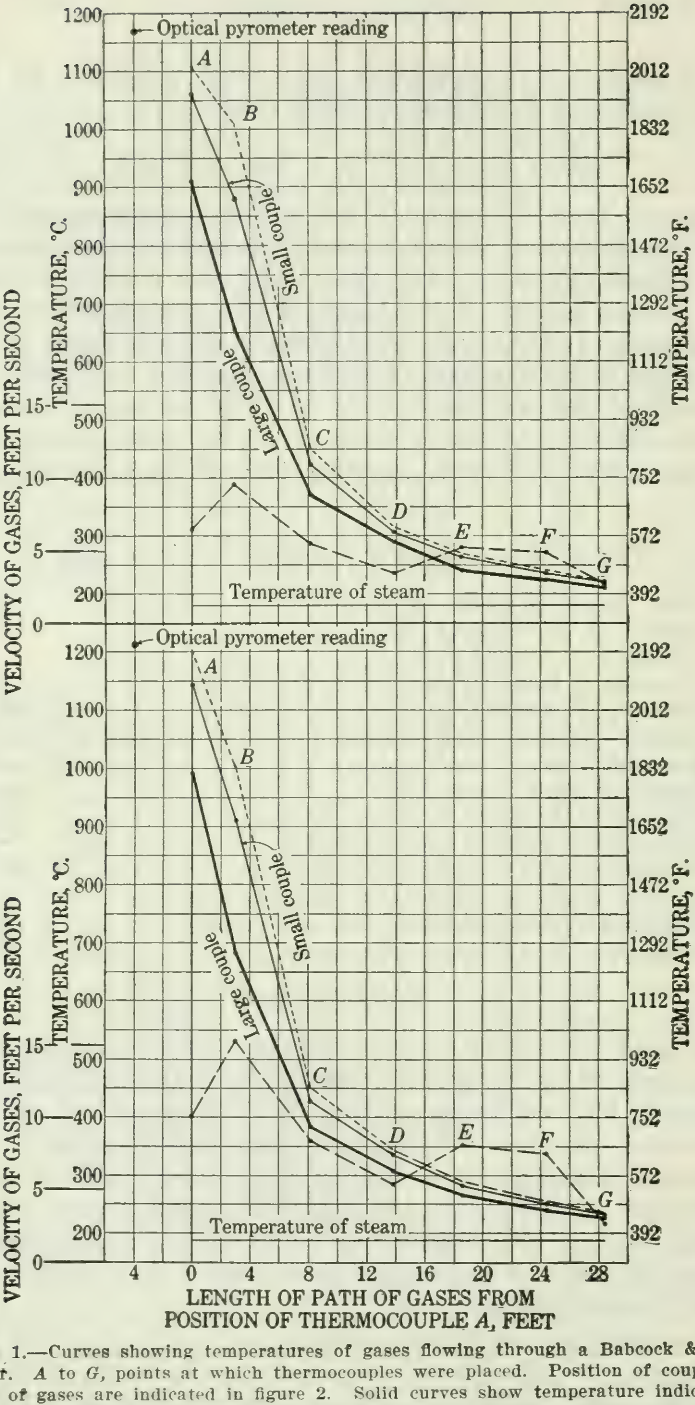

FIGURE 1.—Curves showing temperatures of gases flowing through a Babcock & Wilcox boiler. *A* to *G*, points at which thermocouples were placed. Position of couples and path of gases are indicated in figure 2. Solid curves show temperature indicated by couples; dotted curves, approximate true temperature of gases as computed from experimental data; dashed curve, computed velocity of gases as they pass through boiler setting. Upper and lower diagrams show similar data for two different initial temperatures. Large dot shows temperature obtained with optical pyrometer sighted through one of the gas burners against bridge wall; line of sight is indicated in figure 2.

Heating surface of tubes……square feet	1, 897
Number of steam drums	1
Length of steam drum……feet	22
Diameter of steam drum……inches	42
Approximate effective heating surface of steam drum and water legs……square feet	134

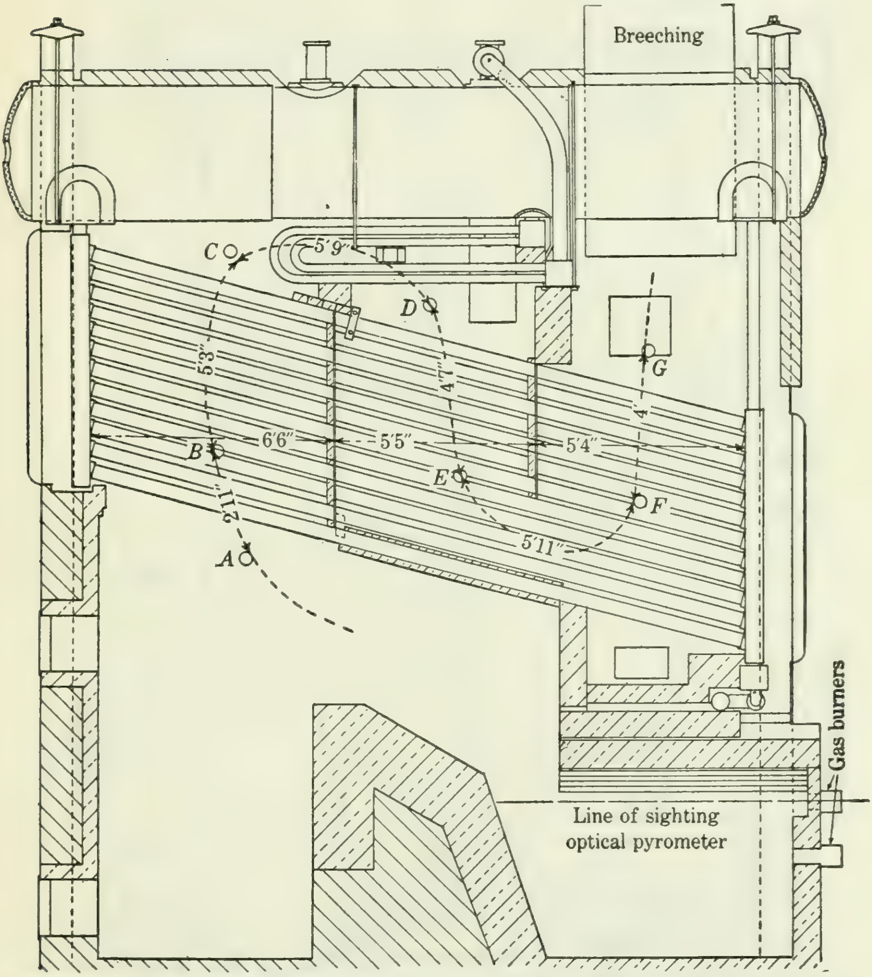

FIGURE 2.—Cross section of Babcock & Wilcox boiler, fired with natural gas. *A* to *G*, position of thermocouples. Dotted line shows path of gases.

TESTS WITH DOUBLE-PASS HEINE BOILER.

The results of experiments with a double-pass Heine boiler in the plant of the experiment station of the Bureau of Mines at Pittsburgh, Pa., are shown in figure 5. The boiler, shown in cross section in figure 6, was connected to an experimental hand-fired furnace, which discharged the hot products of combustion under the rear end of the boiler. The usual bridge wall extended to the lowest row

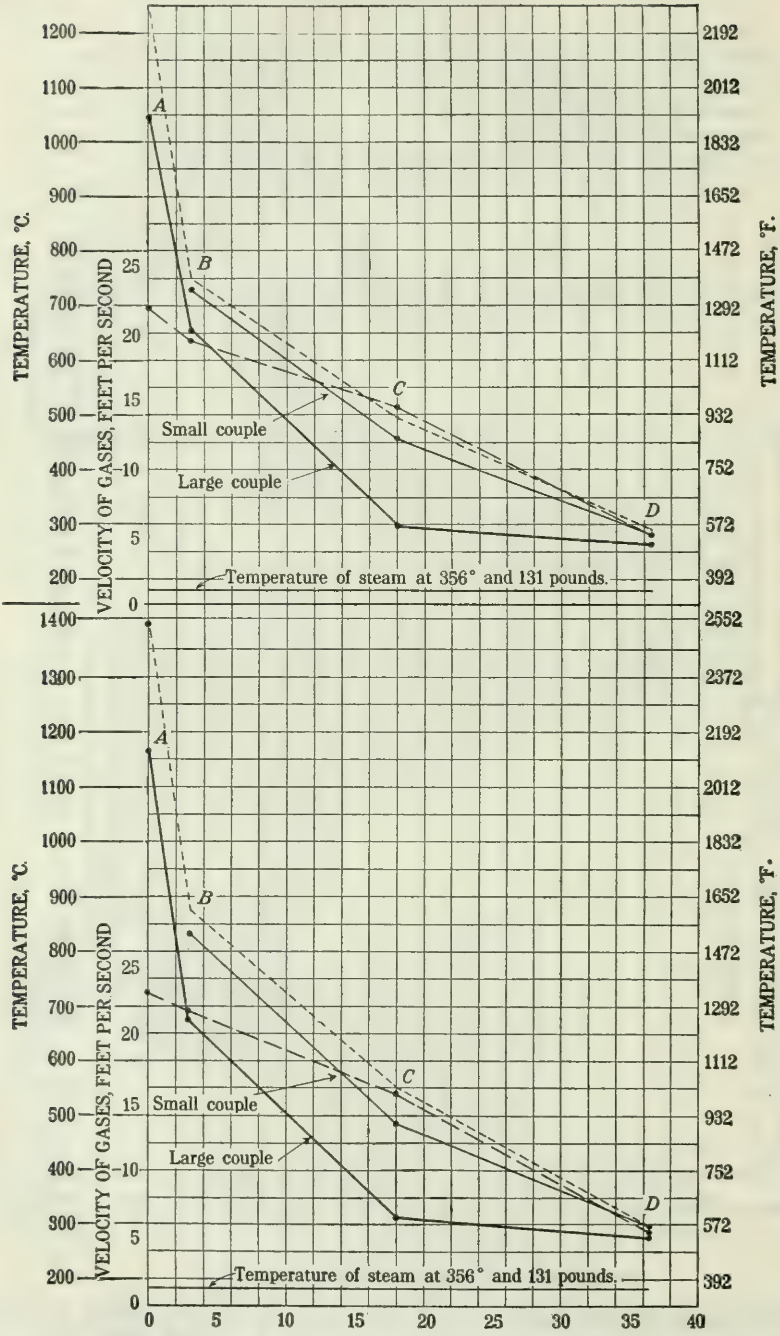

FIGURE 3.—Curves showing temperatures of gases flowing through a single-pass Heine boiler. Positions of thermocouples and path of gases are indicated in figure 4. Solid curves show temperatures indicated by couples; dotted curve, approximate true temperature of gases as computed from experimental data; dashed curve, computed velocity of gases as they pass through boiler setting. Upper and lower diagrams show similar data for two different initial temperatures.

of tubes. The firing doors and the ash-pit doors in front of the boiler were closed air-tight. The positions of the thermocouples are indicated by the small circles designated *A* to *F*. The principal dimensions of this boiler follow:

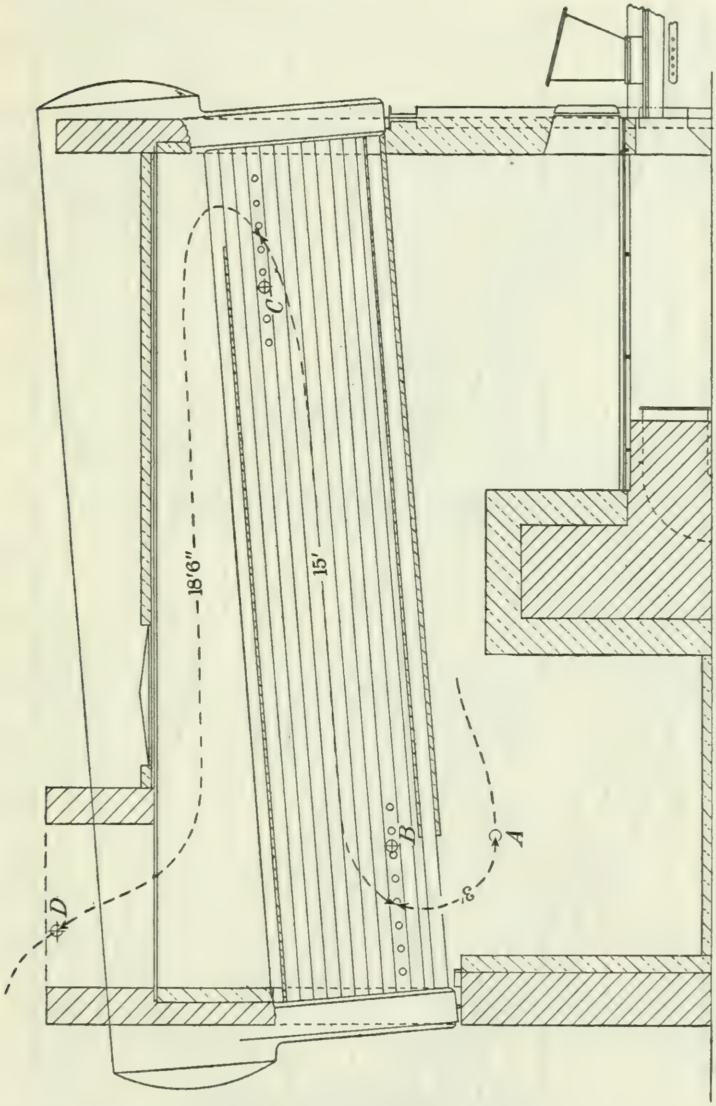

FIGURE 4.—Single-pass Heine boiler, equipped with Jones underfeed stoker. *A* to *D*, positions of thermocouples.

Dimensions of double-pass Heine boiler used in tests.

Total number of tubes	116
Number of horizontal rows	11
Diameter of tubes ... inches	3.5
Length of tubes ... feet	18

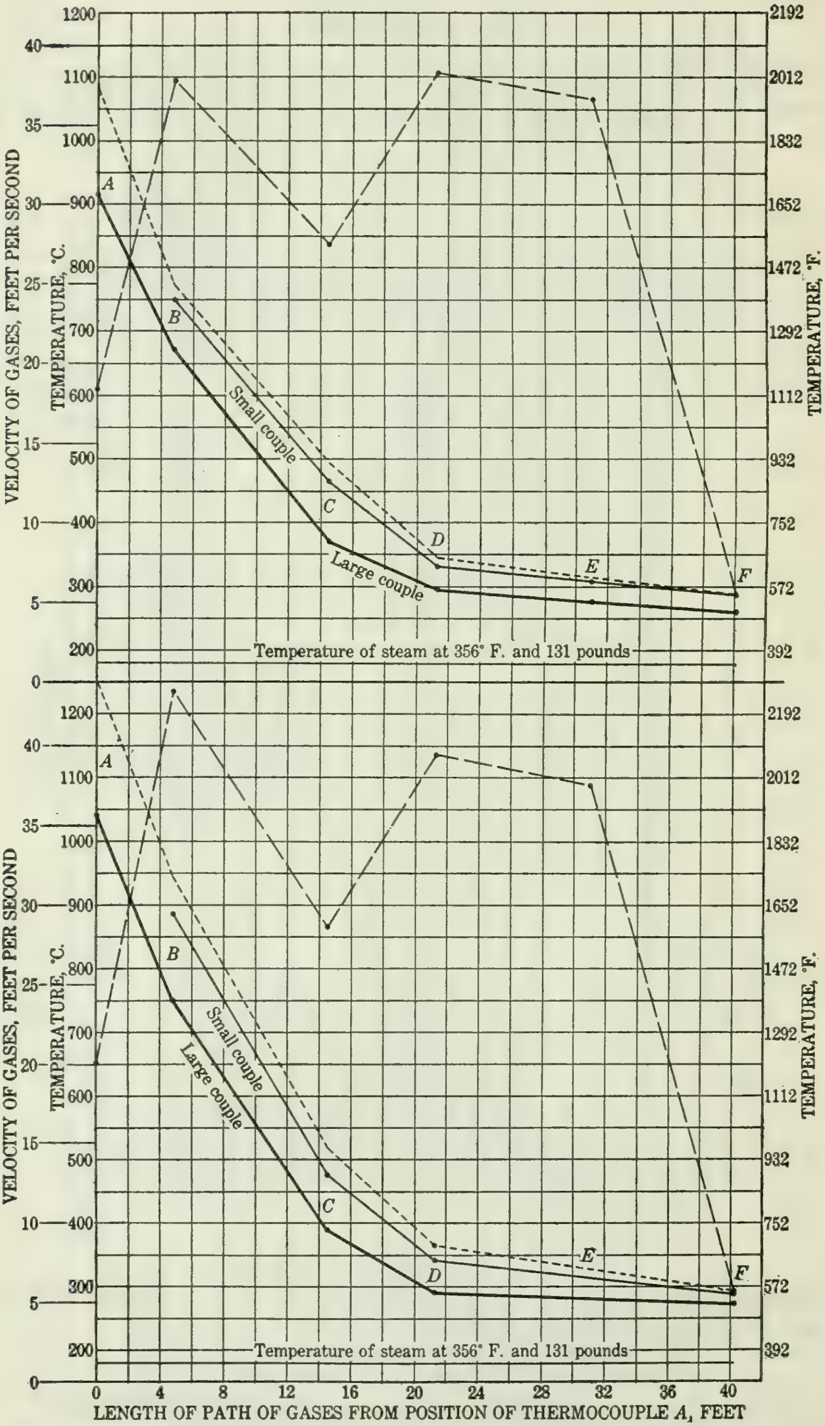

FIGURE 5.—Curves showing temperatures of gases flowing through a double-pass Heine boiler. Positions of thermocouples and path of gases are indicated in figure 6. Solid curves show temperatures indicated by couples; dotted curve, approximate true temperature of gases as computed from experimental data; dashed curve, computed velocity of gases as they pass through boiler setting. **Upper and lower diagrams show similar data for two different initial temperatures.**

Heating surface of tubes ..... square feet..	1,897
Number of steam drums	1
Length of steam drum ..... feet..	22
Diameter of steam drum ..... inches..	42
Approximate effective surface of drum and legs.. square feet..	103

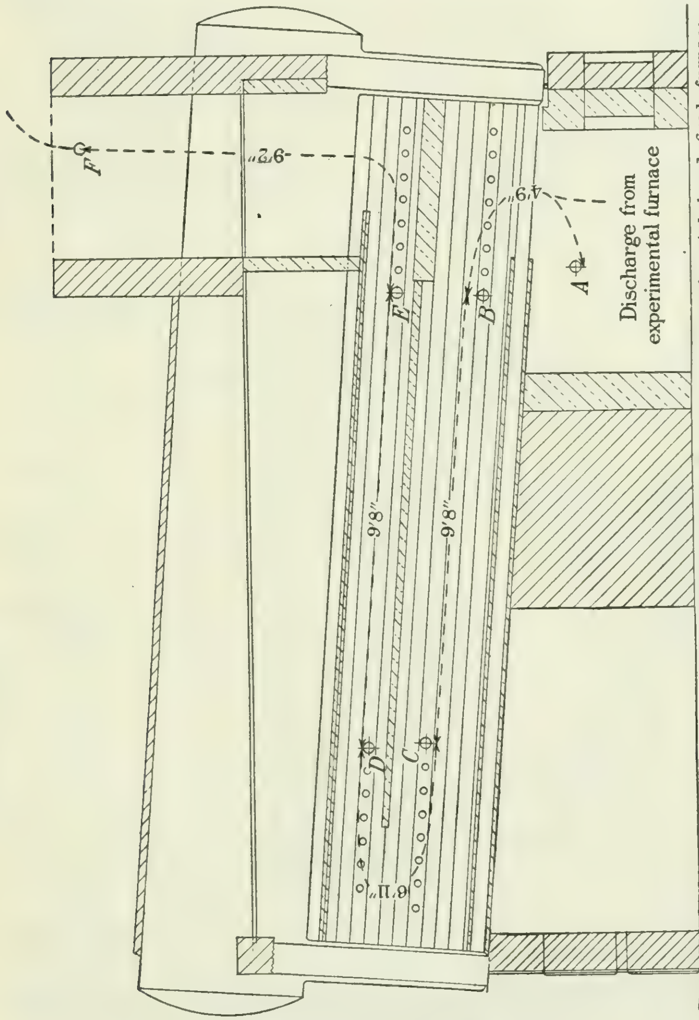

FIGURE 6.—Cross section of double-pass Heine boiler, connected to experimental hand-fired furnace. *A* to *F*, positions of thermocouples. Dotted line shows path of gases.

TESTS WITH PARKER BOILER.

The results of experiments with a Parker boiler in the power plant of the experiment station of the Bureau of Mines at Pittsburgh, Pa., are shown in figure 7. A cross section of the boiler is shown in figure 8. The boiler was equipped with a chain-grate stoker. The positions of the thermocouples are indicated by the small circles designated *A* to *D*. The hot junctions of the couples were within 6

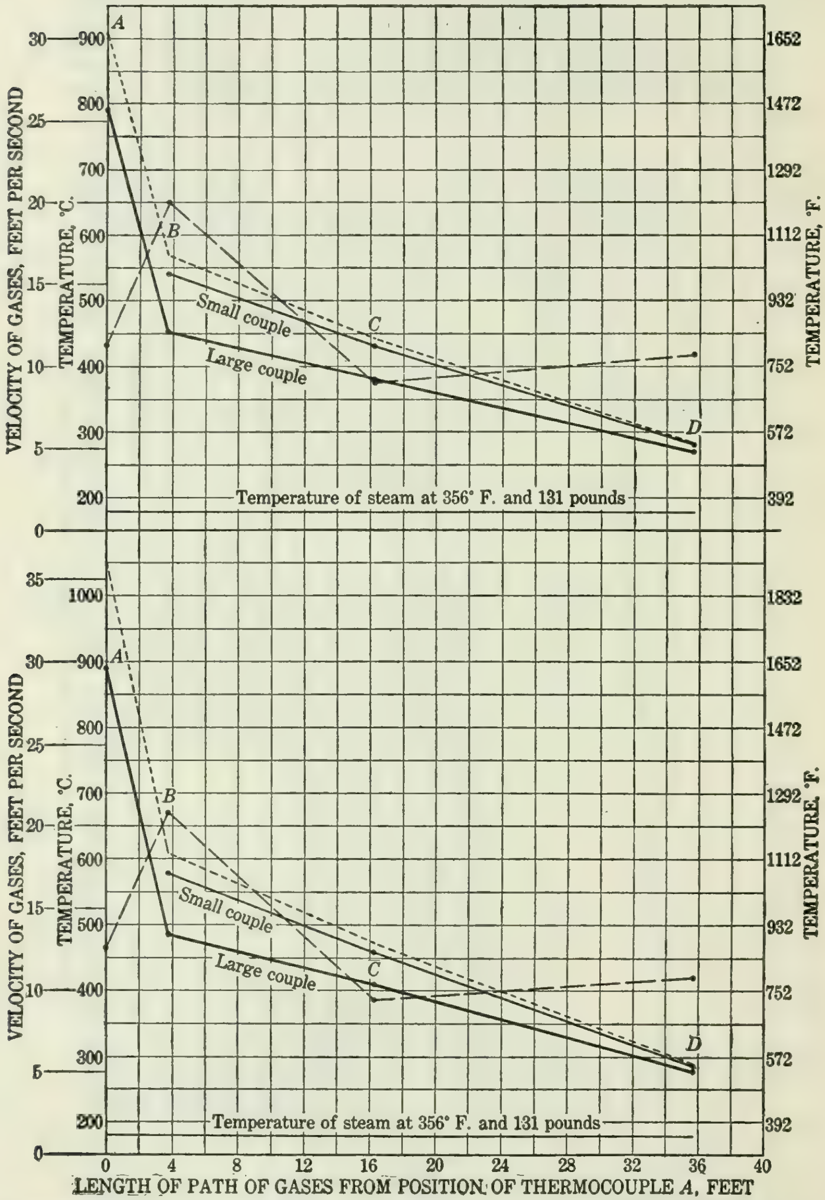

FIGURE 7.—Curves showing temperature of gases flowing through a Parker boiler. Positions of thermocouples are indicated in figure 8. Solid curves show temperatures indicated by thermocouples; dotted curves, approximate true temperature of gases as computed from experimental data; dashed curve, computed velocity of gases as they pass through boiler setting. Upper and lower diagrams show similar data for two different initial temperatures.

inches of a point midway between the side walls. The principal dimensions of the boiler are shown in the following table:

Dimensions of Parker boiler used in tests.

Total number of tubes	112
Number of horizontal rows	8
Number of vertical rows	14
Diameter of tubes, inches	4
Length of tubes, feet	18
Heating surface of tubes, square feet	2, 150
Number of steam drums	1
Length of steam drum, feet	20
Diameter of steam drum, inches	48
Approximate effective surface of steam drum, square feet	50

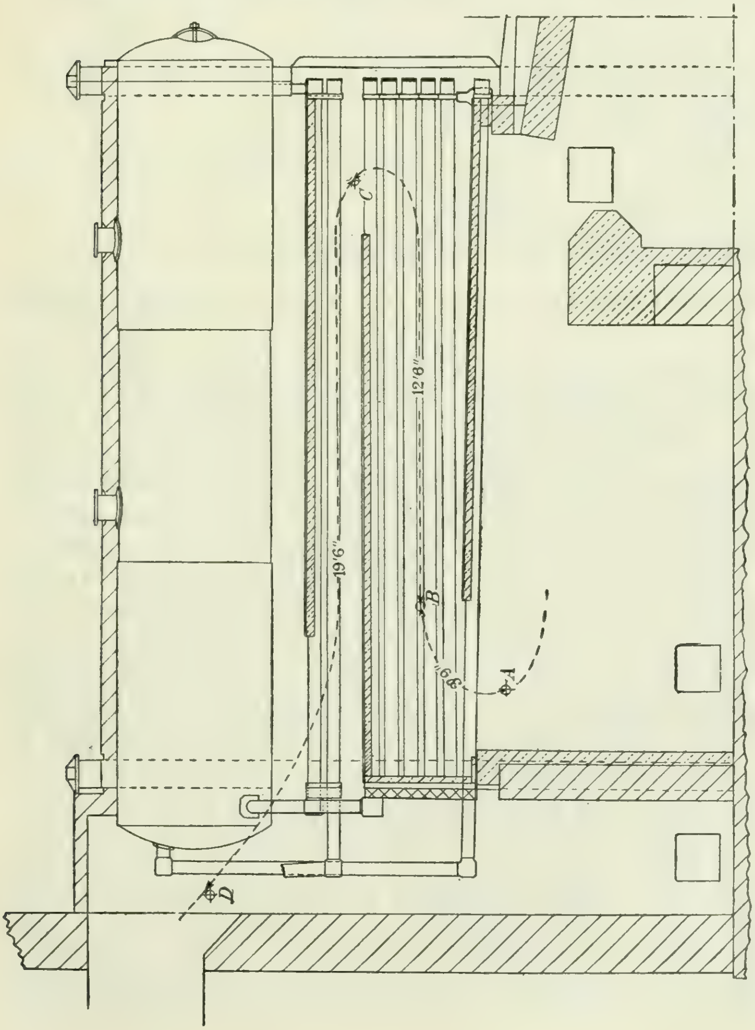

FIGURE 8.—Cross section of Parker boiler. Boiler was equipped with chain-grate stoker. *A* to *D*, positions of thermocouples. Dotted line shows path of gases.

TESTS WITH STIRLING BOILER.

Figure 9 shows results of tests with a Stirling boiler in the power plant of the Carnegie Technical Schools, Pittsburgh, Pa. A cross section of the boiler, which was fired with natural gas, is shown in figure 10. The positions of the thermocouples are indicated by the small circles designated *A* to *F*. The hot junctions of the couples were within 6 inches of a point midway between the side walls. The dimensions of the boiler were as follows:

Dimensions of Stirling boiler used in tests.

Total number of tubes	240
Diameter of tubes, inches	$3\frac{3}{16}$
Number of tubes across front of boiler	20
Total heating surface of tubes, square feet	2, 850
Diameter of steam drums, inches	42
Length of steam drums, feet	$12\frac{1}{2}$
Diameter of mud drum, inches	42
Length of mud drum, feet	10
Approximate effective surface of drums, square feet	200
Number of coils in superheater	32
Length of coils in superheater, feet	9
Diameter of pipe in coils of superheater, inches	4

DESCRIPTION OF THERMOCOUPLES USED TO DETECT RADIATION ERROR.

In the measurement of temperatures two kinds of couples were used: Copper-constantan couples for temperatures below 500° C., and platinum and platinum-rhodium couples for all temperatures higher than 500° C. Two of the same kind of couples were clamped together. In each of these twin couples the wires of one couple at the hot junction were 0.008 inch in diameter, and the hot junction of the other couple consisted of tubes approximately 0.5 inch in diameter. The construction of the twin couples is shown in figure 11; the upper half of the figure represents the copper-constantan twin couple, and the lower half the platinum and platinum-rhodium twin couple.

The leads of the small couples of both kinds were made of wires 0.025 inch in diameter. To one end of these wires were welded small pieces of wire 0.008 inch in diameter, these small wires forming the hot junctions. The object of using heavier wire beyond about half an inch from the hot junction was to strengthen the couple and to prevent sagging of the exposed part. The thicker wires were insulated with small porcelain tubes. In the copper-constantan couples these tubes were placed in standard $\frac{3}{8}$-inch iron pipe, and extended the full length of the couple, to the cold junction. In the small platinum couple the porcelain tubes were placed in a short piece of fused silica tube fitted into the end of a water-cooled holder about

5 feet long. The holder was made of three concentric thin-walled copper tubes. The smallest of these contained the thermocouple wires with their insulating porcelain tubes. By proper connections water entered the annular space between the inner and the middle copper tube, flowed to the hot end, and returned between the middle and the outer tube to the outlet.

The outside tube was only three-fourths inch in outside diameter, making the holder of convenient size for manipulation. These water-cooled holders took the place of expensive and brittle porcelain tubes, which would have broken easily when used under the given conditions, and served their purpose well.

The large copper-constantan couple was made of a copper tube 0.550 inch in outside diameter and having a wall 0.012 inch thick. Into one end of this tube was rolled a cup-shaped copper plug. The hot junction was made by peening into this plug a constantan wire 0.025 inch in diameter. This wire was led through the copper tube, from which it was insulated with glass tubing, to the cold junction placed at the other end of the copper tubing. This method of making the hot junction was mechanically satisfactory and calibration before and after the couple was used showed that its thermal electromotive force remained constant. The outside surface of the copper tube and the surface of the copper plug at the end of it received and radiated the heat.

The large platinum couple was made of wires 0.025 inch in diameter insulated by small porcelain tubes. The hot-junction end of the couple was placed in a silica tube, 0.450 inch in outside diameter and about 11 inches long, and having one end closed. The open end of this tube was fitted into a water-cooled holder as described in the preceding paragraphs. The outside surface of the tube received and radiated heat, so that, neglecting the difference in the coefficient of emissivity, the reading obtained with this construction was about the same as would have been obtained with a couple made of a large platinum tube similarly to the large copper-constantan couple. The silica tube was sufficiently long that the temperature drop due to heat conduction along the tube to the water-cooled holder was so small as to be negligible. It is well to state in this connection that the Bureau of Standards, when calibrating thermocouples at high temperatures, uses an immersion of 25 cm., or about 9$\frac{7}{8}$ inches.

The cold junction of each couple was placed in a water bath contained in a glass vessel clamped to the cold end of the couple. The vessel, a piece of glass tubing 2 inches in diameter and about 6 inches long, was closed at both ends with rubber stoppers having perforations in which were inserted small glass tubes extending from one stopper to the other. Through the small glass tubes were passed the wires of the couples, the cold junction being placed midway between the two stoppers. From the cold junctions the copper connections

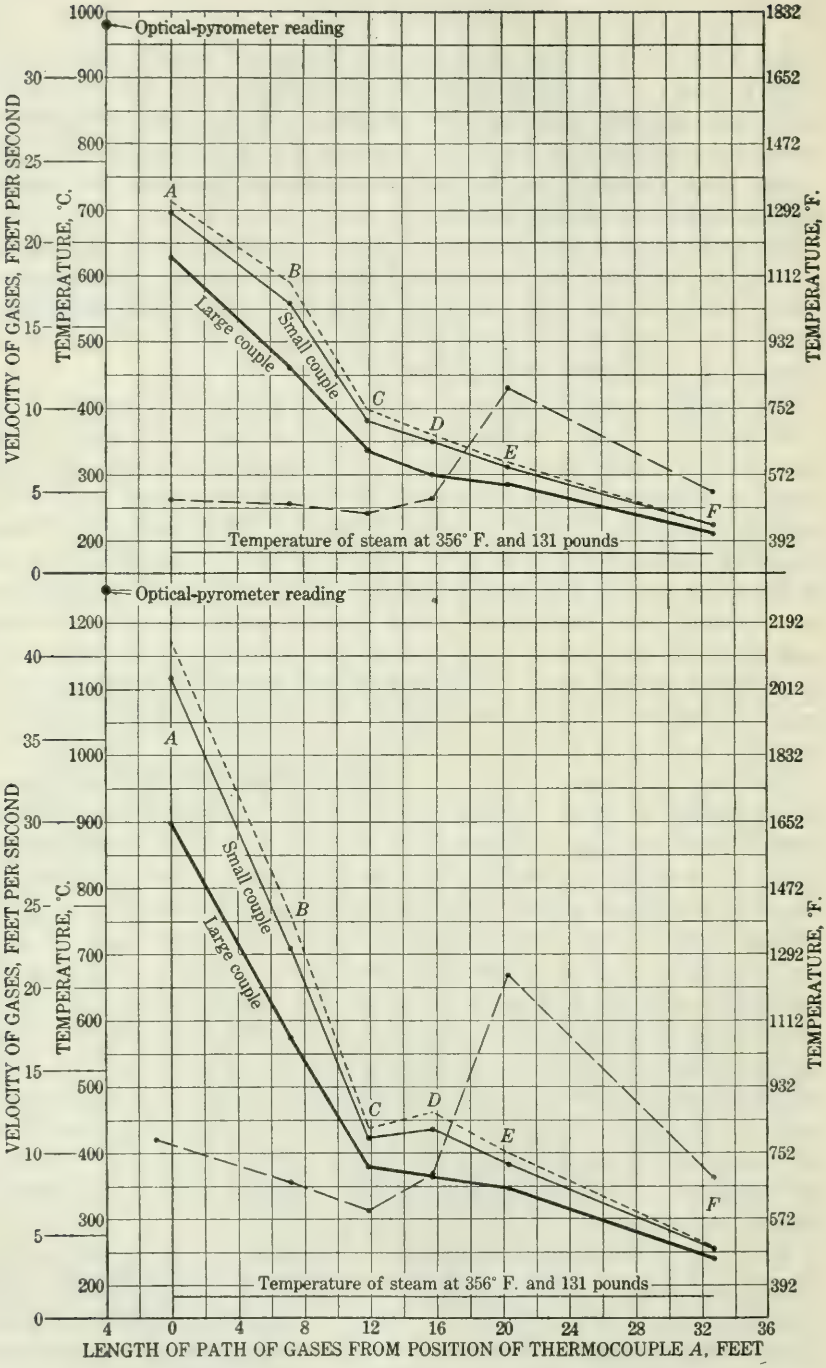

Figure 9.—Curves showing temperatures of gases flowing through a Stirling boiler. Positions of thermocouples are indicated in figure 10. Solid curves show temperature indicated by thermocouples; dotted curve, approximate true temperature of gases as computed from experimental data; dashed curve, computed velocity of gases as they pass through boiler setting. Upper and lower diagrams give similar data for two different initial temperatures. Large dot shows temperature of bridge wall as measured by optical pyrometer sighted through one of the burners.

were led to binding posts fastened to a fiber board. A thermometer was inserted through the free end stopper for the purpose of measuring the temperature of the bath.

A portable Leads & Northrup potentiometer was used to read the millivoltage of the couples, thus giving the temperatures.

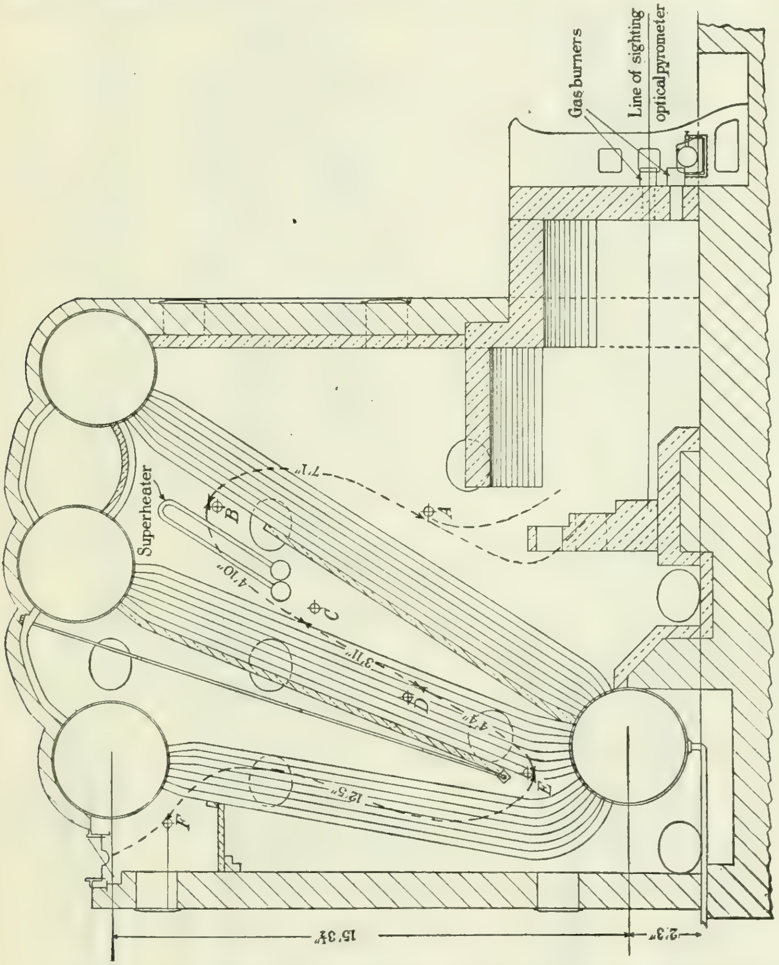

FIGURE 10.—Cross section of Stirling boiler, fired with natural gas. *A* to *F*, positions of thermocouples. Dotted line indicates path of gases.

REDUCING THE RADIATION ERROR BY SCREENING THE INSTRUMENT.

The radiation error can be reduced by screening the instrument from direct exposure to cold surfaces. The screens must be placed between the instrument and the cold surfaces in such a way that the hot gases come in contact with both sides of the screen. Screens of this kind were used in many of the steaming tests made by the Bureau of Mines and are fully described in Bulletin 23[a] and Bulletin 97.[b]

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[a] Breckenridge, L. P., Kreisinger, Henry, and Ray, W. T., Steaming tests of coal and related investigations: Bull. 23, Bureau of Mines, 1912, pp. 32–33.

[b] Kreisinger, Henry, and Ovitz, F. K., Sampling and analysis of flue gases: Bull. 97, Bureau of Mines, 1915, p. 48.

By the use of such screens the radiation error can be reduced to less than one-half of the unprotected instrument. However, in many types of commercial apparatus the use of screens in making temperature measurements is impracticable.

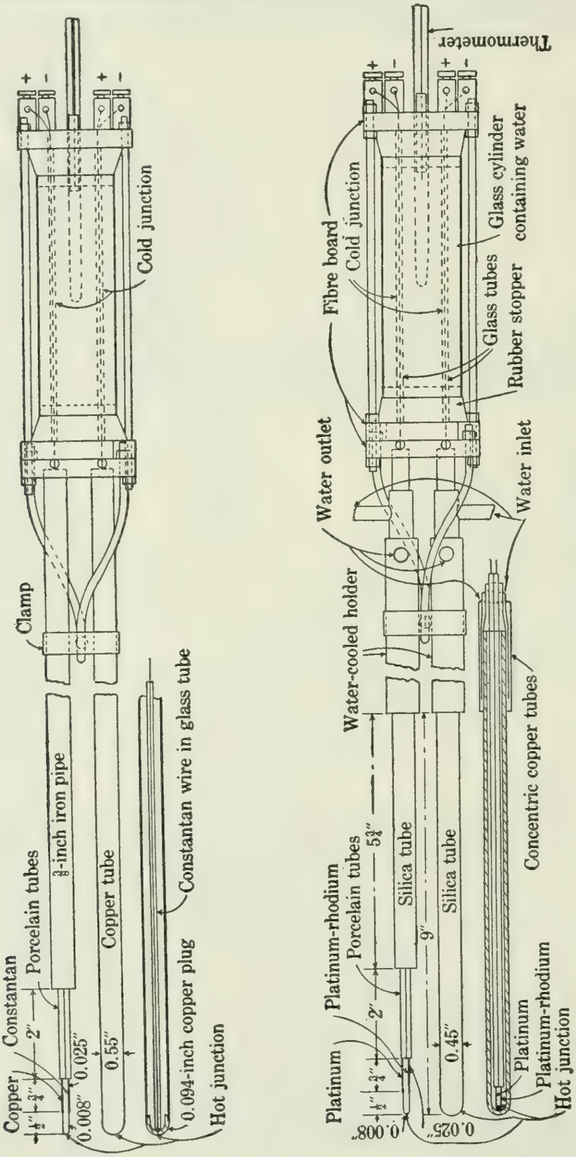

FIGURE 11.—Construction of twin couples used in temperature measurements shown in figures 1, 3, 5, 7, and 9. Upper half of the figure shows construction of the copper-constantan twin couples; lower half shows the construction of the platinum and platinum-rhodium twin couples.

DISADVANTAGE OF USING EXPOSED COUPLES.

It has been shown in the preceding discussion that a thermocouple having its hot junction exposed to the gases has a much smaller radiation error than one protected by a porcelain or a fused silica tube. The use of the exposed couple has the drawback of the metal being liable to contamination if the gases are not clean. The impurities in the gases may combine with the metal, thus changing its nature. Carbon monoxide will form carbides with platinum, but will not affect a copper-constantan couple. The danger of the exposed part of the couple being contaminated is particularly serious when the temperature of very hot gases containing slag-forming constituents is being measured as in all apparatus using coal as fuel, and in metallurgical furnaces where the gases may contain fumes from the molten metal. Prolonged use of an exposed couple under such conditions is sure to impair its accuracy. If it is desirable to use an unprotected couple it should not be left in the gases any longer than is necessary to take a reading. The thermocouple junction, being very small, is heated to full temperature almost instantaneously, so that the reading can be taken immediately after the couple is inserted into the stream of gases; it should then be withdrawn. If the products of combustion are clean gases, such as result from the burning of natural gas, such precautions are not necessary.

A copper-constantan couple that was placed in flue gases, as suggested on page 57, showed no change in calibration, even after the wires were partly oxidized by several months of use.

VARIATION OF TEMPERATURE OF GASES AT DIFFERENT POINTS IN THE SAME CROSS SECTION.

Even though it may be possible by the use of a fine couple to obtain the correct temperature of the gases at any one point, obtaining the average temperature of the gases at any given cross section of their path is difficult, because the temperature may vary widely at different points of the same cross section. These variations are due chiefly to stratification of the gases, unequal cooling, and perhaps infiltration of air which tends to cool the gas next to the wall.

Variations in temperature between different points of the same cross section of a boiler setting are shown in figures 12 to 15.

EXPERIMENTS WITH BABCOCK & WILCOX BOILER.

Figure 12 shows the variation obtained when the twin couples at *E* and *G* in the Babcock & Wilcox boiler (see fig. 2, p. 13) were moved in equal steps from their central position. The twin couple at *E* was moved 1 inch at a time over a distance of 1 foot and the temperature indicated by both the small and the large couple was read for each position. The upper two curves of the figure represent these temperature readings, the small couple reading higher than the large one. The small couple showed two kinds of variation: A small drop in temperature for every 6 or 7 inches, corresponding probably to the spacing of the tubes, and a constant gradual drop of temperature as the couples were moved nearer to the wall. The large couple shows only this latter variation.

The twin couple at *G* was moved in steps of 6 inches. With this couple only the constant drop in temperature is apparent, the variation due to spacing of tubes not being noticeable.

The couples were moved and the readings taken in rapid succession, the entire series with each couple not taking more than 4 or 5 minutes. During these measurements the furnace conditions were kept constant, which was comparatively easy because of the control of the gas burners.

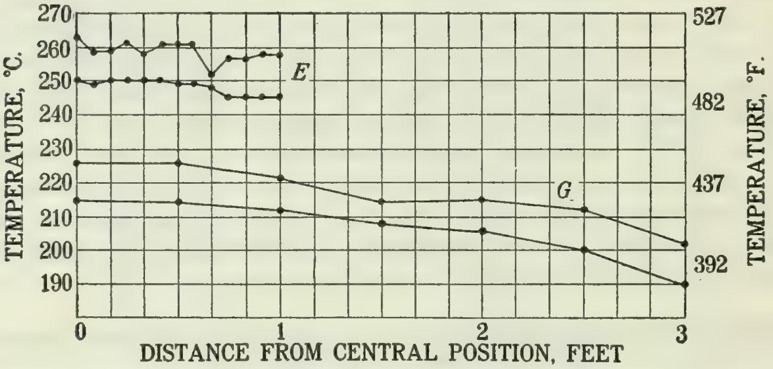

Figure 12.—Curves showing variations of temperature at different points of the same cross section in a Babcock & Wilcox boiler fired with natural gas. Upper pair of curves represents temperatures obtained by moving twin couple at *E* 1 inch at a time from central position; lower pair, temperatures obtained by moving twin couple at *G* 6 inches at a time. Upper curve of each pair represents temperature indicated by small couple; lower curve, temperature indicated by large couple.

EXPERIMENTS WITH STIRLING BOILER.

Figure 13 shows the variation in temperature when the twin couple at *D* in the Stirling boiler (see fig. 10, p. 23) were moved 1 inch at a time from its central position. The upper curve gives the temperatures indicated by the small couple, and the lower curve, the temperatures shown by the large couple. Both couples show temperature variation apparently due to the spacing of the tubes, and also a gradual temperature drop as the hot junctions are moved away from the center. While these readings were taken the furnace conditions were kept as nearly constant as possible by using the same number of gas burners with the same adjustment. The highest and the lowest temperatures recorded by either of the couples differ by 50° C., whereas the small couple always read about 50° C. higher than the large one. These variations show how little dependence can be placed on a reading obtained with a thermocouple inserted at random into a boiler setting.

EXPERIMENTS WITH SINGLE-PASS HEINE BOILER.

Figure 14 shows the temperature variation when the small couples at *B* and *C* in the standard single-pass Heine boiler, shown in figure 4 (p. 15), were moved in steps of 6 inches, the couples being placed in the same stay-bolt holes as they were for obtaining the data shown by the curves in figure 3 (p. 14). These 6-inch steps are indicated in figure 4 by the small circles.

Couple *B* showed a considerable range of temperature variation. The maximum temperature, which was at a point about 2 feet from the inside of the water leg, was 430° C. higher than that at a point 4 feet from the water leg. This wide variation was undoubtedly caused by the position of the end of the lower baffle and the sudden turn of the gases. It seems that immediately above the lower baffle there was a layer of comparatively inert gas which had a temperature much lower than that of the stream of moving gases.

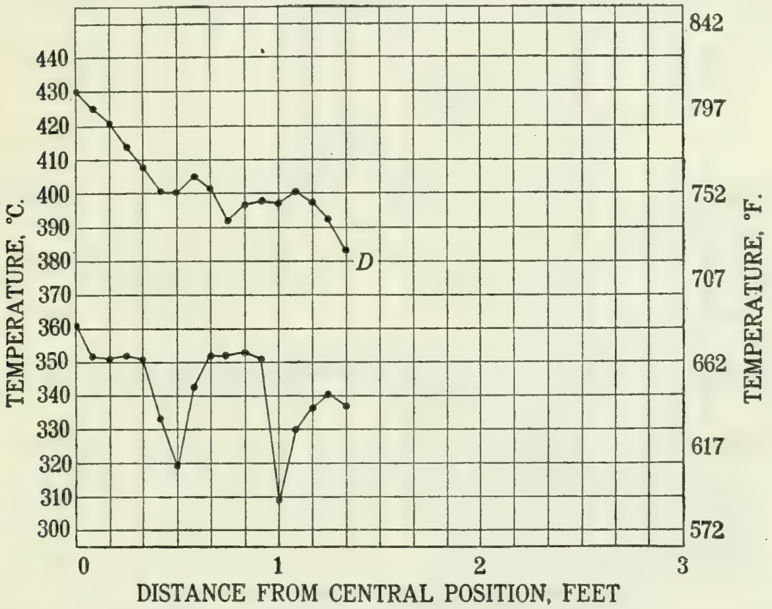

FIGURE 13.—Curves showing variations of temperature at different points of the same cross section in a Stirling boiler fired with natural gas. Readings were obtained by moving the twin couple at *D* 1 inch at a time from its central position. Upper curve represents temperature indicated by small couple; lower curve, temperature indicated by large couple.

Couple *C* showed a steady rise in temperature as the hot junctions were moved away from the water leg, but after a point about 2 feet from the water leg was reached the temperature remained nearly constant. The extreme variation in temperature shown by this couple was about 200° C.

EXPERIMENTS WITH DOUBLE-PASS HEINE BOILER.

Figure 15 shows the temperature variation under similar conditions in the two-pass Heine boiler attached to the hand-fired experimental furnace. Although with this apparatus the furnace conditions could not be kept as constant as with the Jones underfeed stoker, the thermocouples when moved into different position showed less variation in temperature than was found in the single-pass Heine boiler with the Jones stoker. The extreme variation shown by the couple at *D* was about 100° C. This smaller temperature variation was probably due to the higher velocity of the gases, which facilitated mixing and therefore a more uniform temperature. Readings were taken only with the small couples. The position for each reading is indicated in figure 6 (p. 17) by the small circles.

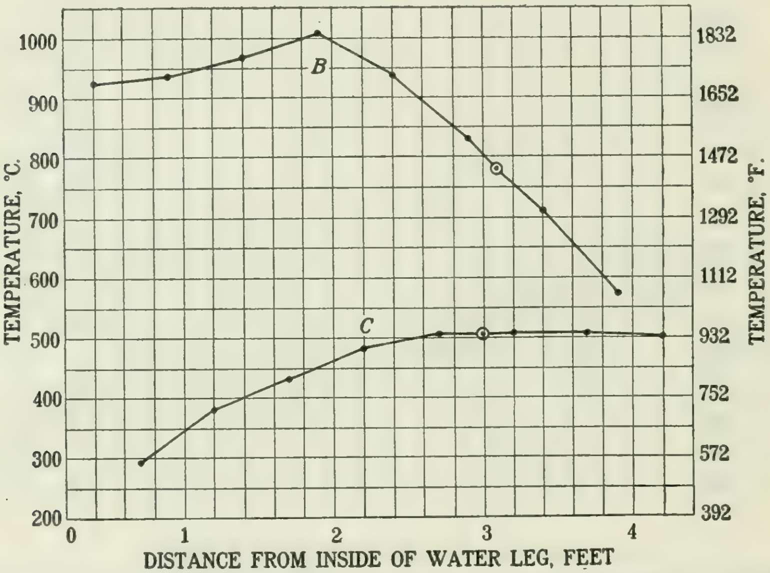

FIGURE 14.—Curves showing variations of temperature at different points in a standard single-pass Heine boiler equipped with a Jones underfeed stoker. Upper curve was obtained by moving small couple at *B* in 6-inch steps to a point 4 feet from inside of water leg; lower curve, by moving small couple at *C* in same way. Positions for each reading are shown by the small circles in figure 4; furnace conditions were kept as uniform as possible. Large circles on curves show positions of couples when data for figure 3 (p. 14) were obtained.

No readings for different position of the hot junctions were taken in the Parker boiler.

FLUCTUATION OF TEMPERATURE AT ANY ONE POINT.

The temperature of the gases at any one point in the boiler setting may fluctuate rapidly over a wide range, even though the furnace conditions may be kept very uniform. The fluctuations in temperature obtained by taking readings every 2 seconds with two of the small couples in the Babcock & Wilcox boiler are shown in figure 16. The upper curve connects points representing readings taken with the small thermocouple of the twin couple at *A* (fig. 2) and the lower curve those obtained from readings taken with the small couple of the twin couple at *C* (fig. 2). The two series of readings were

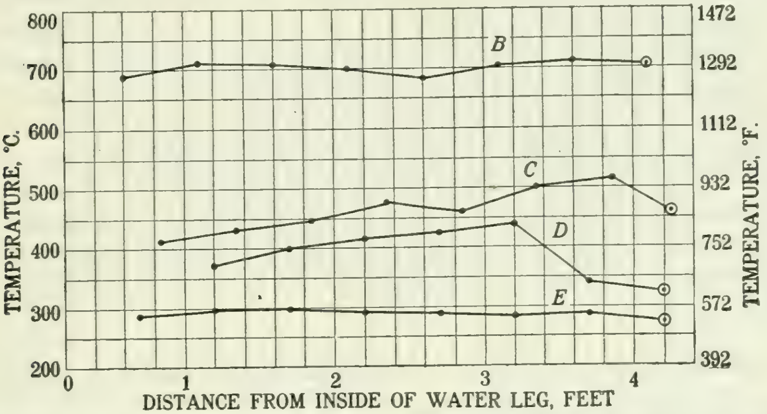

FIGURE 15.—Curves showing variations of temperature at different points in a double-pass Heine boiler receiving hot gases from a hand-fired experimental furnace. The four small couples, *B, C, D,* and *E*, were moved into different positions (shown in fig. 6, p. 17, by the small circles) 6 inches apart and a reading was obtained for each position. Each curve gives temperature indicated by couple designated by the letter. Large circles at right end of curves show positions of couples when data for figure 5 (p. 16) were obtained.

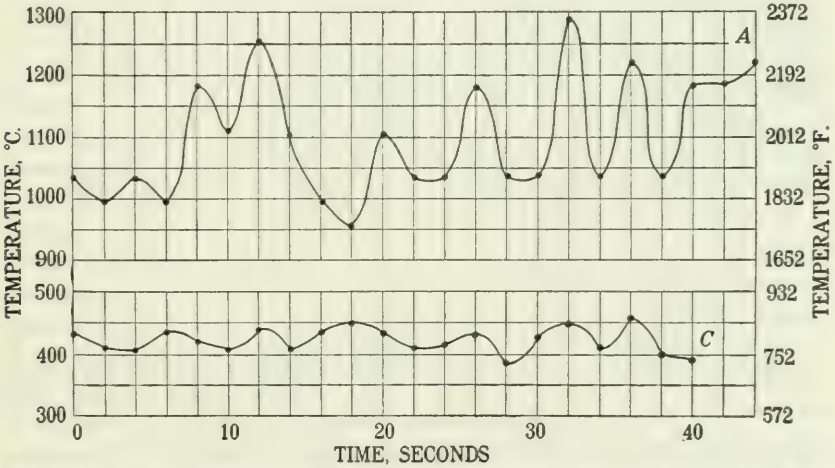

FIGURE 16.—Curves showing fluctuations of temperature at points *A* and *C* in the Babcock & Wilcox boiler shown in figure 2 (p. 13). The fluctuations were obtained by reading the small couples every 2 seconds.

not taken simultaneously, the readings for the lower curve being taken immediately after the readings for the upper curve, but the furnace conditions were kept the same for both series. Only the small couple of each twin showed large fluctuations, the temperature indicated by the large couple, which was noted whenever a reading was made with the small couple, being nearly constant and considerably below the average of that indicated by the small couple. The maximum temperature fluctuation shown by the couple at *A* was about 300° C., the average temperature being about 1,100° C. The couple at *C* showed a temperature fluctuation of about 50° C. and an average temperature of 425° C. This smaller fluctuation was partly due to the lower average temperature and partly to more complete mixing of the gases.

TEMPERATURE DROP OF GASES IN FLOWING THROUGH BOILERS.

TEMPERATURE DROP THROUGH TUBE OF A HORIZONTAL TUBULAR BOILER.

The temperature measurements given in figures 1, 3, 5, 7, and 9 afford a rough comparison of the temperature drop through the various types of water-tube boiler. In order to make this comparison more complete, the temperature drop of the gases passing through a tube of a gas-fired horizontal tubular boiler is shown in figure 17.

The data for the lower set of curves of figure 17 were taken when the initial temperature of the gases was 1,200° C. and the boiler was developing 1 boiler-horsepower on about 5 square feet of heating surface. The upper set of curves is based on data obtained with an initial temperature of 800° C. and when the boiler was generating 1 boiler horsepower on 15 square feet of heating surface. The boiler was operated under a pressure of 120 pounds gage. The boiler tubes were $2\frac{3}{4}$ inches in inside diameter and 20 feet long. Temperature measurements were taken in one of the tubes, at the points indicated in figure 17 by the black dots, with a platinum and platinum-rhodium couple having an exposed hot junction 0.012 inch in diameter. Only the temperatures obtained in the center of the tube are given in the charts, although readings were taken at nine different points along a vertical diameter. The true average temperature of the gases as they passed through the tube was determined partly from the temperature of the gases entering the tube, partly from the average temperature of the gases after they left the tube and partly by correcting for radiation error the measured temperature in the tube. The average velocity of the gases was calculated from their average temperature and from the weight of air and natural gas used as measured with an orifice and a gas meter before the air and gas were fed into the furnace. The average temperature is correct to within less than 5 per cent and the average velocity to within less than 10 per cent.

Near the furnace end of the boiler tube the true average temperature was higher than the indicated temperature at the center of the cross section of the tube. The fact that the true temperature was

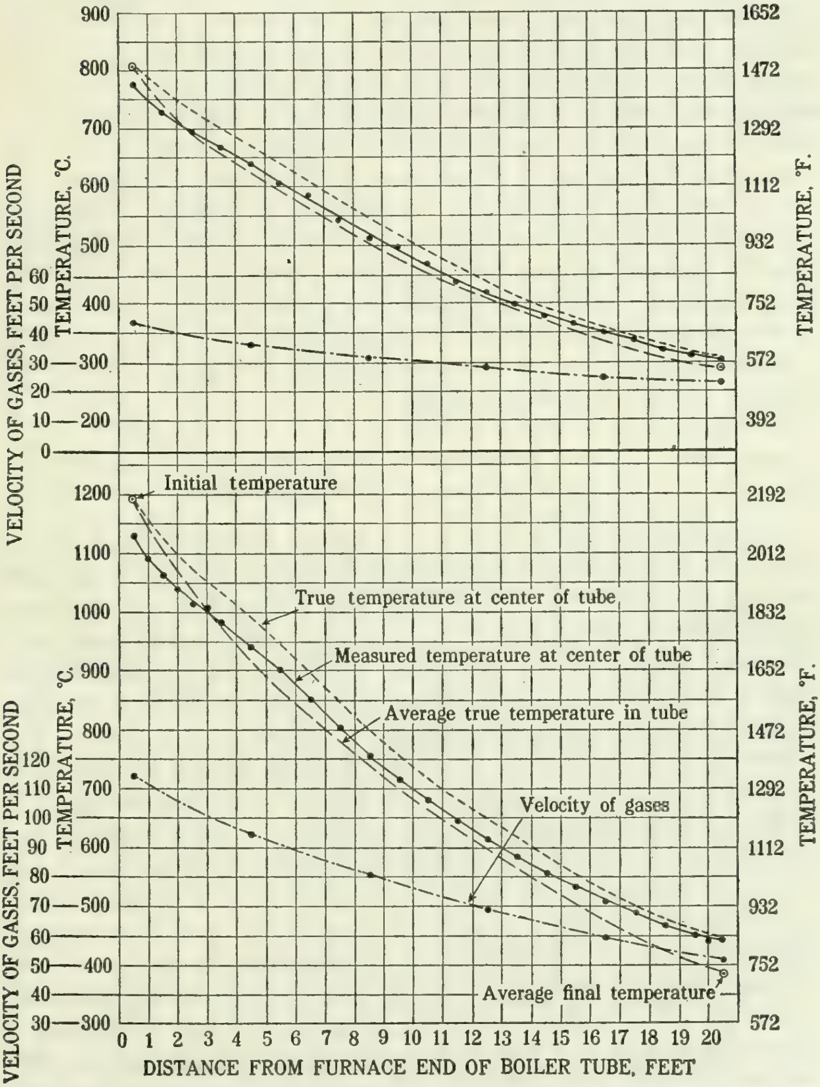

FIGURE 17.—Curves showing variations in temperature of gases flowing through a horizontal tubular boiler, having tubes 2¾ inches in internal diameter, fired with natural gas. ———measured temperature in center of tube. ------ true temperature in center of tube. ——— ——— ——— true average temperature of gases in tube. ———. ———. ——— computed velocity of gases.

higher was due to the high radiation error of the thermocouple, caused by the high temperature difference between the thermocouple and the surfaces surrounding it, and also to the fact that the temperature of the gases across the whole section was nearly uniform, making the average about the same as the temperature at the center. On the other hand, near the exit end the radiation error of the thermocouple was small because of the small temperature difference between the thermocouple and the surfaces surrounding it. In addition the indicated temperature of the gases was much higher at the center than at points nearer to the surface of the tube, so that the average was considerably below the temperature at the center. For these two reasons the average true temperature at the exit end was lower than the indicated temperature at the center of the cross section of the tube. The larger variation in temperature across the diameter of the tube nearer to the exit end is shown in figure 24 (p. 47). These features will be discussed more in detail in a forthcoming paper to be devoted to heat transmission in a fire-tube boiler. In the present paper only enough data is presented to make possible a comparison of the temperature drop of the gases as they flow through boilers of different types.

COMPARISON OF THE TEMPERATURE DROP OF GASES AS THEY FLOW THROUGH BOILERS OF DIFFERENT TYPES.

Comparison of figures 1, 3, 5, 7, 9, and 17 reveals the fact that by far the greater part of the temperature drop occurs in the first one-third of the gas path. This drop is much greater in all the water-tube type of boilers than it is in the fire-tube boiler; and seems to be somewhat greater in the cross-flow type than in the parallel-flow type of boilers. The steeper temperature drop in the first one-third of the gas path of the water-tube types of boilers as compared with the fire-tube boilers is very likely due to more violent mixing of the gases as they flow among the tubes, the flow at right angles to the tubes probably causing better mixing than the parallel flow.

It should be borne in mind that none of the boilers used in these investigations are purely cross-flow or parallel-flow type, inasmuch as in both types successive parts of the gas path are cross flow and parallel flow, as can be easily seen by following the paths indicated in figures 2, 4, 6, 8 and 10. However, the five boilers may be grouped in two classes in which one or the other type of flow predominates. Thus in the Babcock & Wilcox boiler the cross-flow parts of the paths are longer than the parts with the parallel flow; whereas in the Heine and in the Parker boiler the parts with the parallel flow predominate. The curves for the temperature drop through the water-tube boilers have a very pronounced curvature about one-third of the distance from the point where the gases enter among the tubes. The fire-tube boiler gives a much smoother and straighter curve, especially when the initial temperature of the gases is low, then the curve almost approaches a straight line. This great difference between the shape of the curves for the two types of boilers indicates that the process of heat transmission is much more complicated in the water-tube than it is in the fire-tube boilers.

DISCUSSION OF RADIATION ERROR.

CAUSES OF RADIATION IN MEASURING TEMPERATURES OF GASES IN BOILER SETTINGS.

When it is desired to measure the temperature of water or any other liquid, a mercury thermometer is immersed in the liquid and the instrument in time acquires the same temperature as the liquid. If the liquid is hot, heat flows from it into the instrument, and the temperature of the latter rises; if the liquid is cold, heat flows from the instrument into the liquid and the temperature indicated by the instrument falls. When the temperature of the liquid and that of the instrument are equalized, the transfer of heat ceases. The instrument loses no heat except a negligible amount by conduction through the stem to the part not immersed in the liquid, and therefore indicates the true temperature of the liquid.

In measuring the temperature of gases inside of a boiler setting, different conditions are encountered than in measuring liquids. If the same methods are followed as in measuring temperatures of liquid, serious errors may be introduced. The presence of the cold heat-absorbing surfaces of the boiler and the fact that gases when clean are permeable to radiation make equalization of the temperature of the gases and that of the instrument impossible. The heat constantly flows by convection from the gases to the instrument, and from the instrument by radiation to the cold surfaces of the boiler. Thereby a difference between the temperature of the gases and that of the instrument is maintained. The readings obtained under such conditions represent the temperatures of the instrument—the mercury bulb or the hot junction of a thermocouple, as the case may be—and not the temperature of the gases, just as the tubes of a boiler are not at the temperature of the gases, although in direct contact with them. The boiler tube receives heat from the gases by convection and gives it off by conduction and convection to the water. Inasmuch as there must be a drop in temperature for heat to pass from the gases to the tube and also from the tube to the water, the temperature of the tube is between that of the gases and that of the boiler water. In like manner heat is imparted to the thermometer bulb or to the hot junction of the thermocouple by convection from the hot gases, and is radiated from the thermometer or thermocouple to the boiler tube, which is always at a temperature considerably lower than that of the gases. There is a temperature drop from the hot gases to the instrument and another temperature drop from the instrument to the surface of the boiler tube. Therefore, the temperature of the thermometer or the thermocouple is not the same as that of the gases, but is somewhere between the temperature of the gases and that of the boiler tube. In other words, the temperature of the measuring instrument is always lower than that of the moving gases.

Where the gases flow through a passage surrounded by surfaces hotter than the gases, the flow of heat is reversed and the temperature of the measuring instrument is higher than that of the gases. Such conditions occur in heat-regenerating apparatus in metallurgical furnaces, but are seldom met in steam-boiler practice.

How near the temperature of the measuring instrument is to the temperature of the gases in an ordinary boiler setting depends on the relative resistances to the flow of heat from the gas to the instrument and from the instrument to the boiler tube. When the temperature indicated by the instrument is constant, the amount of heat imparted to it by the gases is equal to the amount radiated from it to the tube. If the resistance to the flow of heat from the gases to the instrument is very small as compared to the resistance from the instrument to the boiler tube, the temperature drop is also very small and the temperature indicated by the instrument is very near that of the gases. If, however, the first-named resistance is high as compared with the second one, the temperature drop from the gases to the instrument is high, and the temperature of the instrument will be near that of the boiler tube.

FACTORS AFFECTING HEAT EXCHANGE.

Now, what determines these resistances, or the ease with which heat flows to the instrument and from it? It has been stated that heat is imparted to the instrument by convection, and flows from it by radiation. It can be shown that the amount of heat imparted to the instrument by convection is approximately proportional to (*a*) the difference between the temperature of the moving gases and that of the surface of the instrument receiving the heat, (*b*) the velocity of the moving gases, (*c*) the density of the gas, and (*d*) the extent of the surface receiving the heat. The amount of heat that is radiated from the instrument is approximately proportional to (*a*) the difference between the fourth powers of the absolute temperature of the instrument and of the boiler tubes, and (*b*) the extent of radiating surface of the instrument. The two quantities of heat can be expressed by two algebraic expressions, as follows:

$$(1) \qquad H_c = C(T - T_1)vgS$$

$$(2) \qquad H_r = K[(T_1)^4 - (T_2)^4]S_1$$

H_c=heat imparted to instrument by convection,
H_r=heat radiated from instrument,
T =temperature of moving gases,
T_1 =temperature of couple,
T_2 =temperature of boiler tubes,
v =velocity of moving gases,
g =density of gases,
S =extent of that part of the surface of the instrument receiving heat by convection,
S_1 =extent of that part of the surface of the instrument radiating heat,
C and K=constants.

In equation *1* the velocity of the gases is proportional to their volume. The volume is proportional to the weight of gases passing a given cross section per unit of time, and also directly proportional to their absolute temperature. The density of the gases is inversely proportional to their absolute temperature. Therefore, in equation *1* the product vg equals Cw, where w is the weight of gases, and C is a constant. Equation *1* then takes the form $H_c = C(T - T_1)wS$.

The temperature of the instrument is read when it is nearly constant; that is, when the quantity of heat the instrument receives from the hot gases is equal to the quantity that it radiates to the surrounding cooler surfaces, or when $H_c = H_r$, or,

$$(3) \qquad C(T - T_1)wS = K[T_1^4 - T_2^4]S.$$

In equation *3* the difference $T - T_1$ is the radiation error; that is, it shows how much lower the temperature of the measuring instrument is than the temperature of the gases. By studying this equation the effect of the various factors on the magnitude of the radiation error can be predicted. Thus if T, the temperature of gases, is raised the value of the temperature factor $T - T_1$ on the left side of the equation becomes larger, and therefore the rate of heat impartation to the instrument by convection is increased. The rate of heat radiation from the instrument is not directly affected, so that more heat is received by the instrument than is given off, and therefore its temperature T_1 rises. The rise in T_1 increases the value of the temperature factor $(T_1)^4 - (T_2)^4$ in the right side of the equation, thereby increasing the rate of heat radiation from the instrument. At the same time the rise of temperature of the instrument T_1 reduces the value of the temperature factor $T - T_1$ in the left side of the equation, thus reducing the rate of heat impartation to the instrument. The temperature of the instrument T_1 continues to rise until equilibrium is established and the values of the two sides of the equation are equal. However, owing to the fact that in the right side of the equation T_1 enters as the fourth power and in the left side only as the first power, the rise in T_1 is much smaller in proportion to the rise of T, the temperature of the gases, when equilibrium is reached. This means that the radiation error is much larger when the temperature of the gases is high than when their temperature is low.

The weight of the gases, w, directly affects only the left side of the equation; that is, the amount of heat imparted to the instrument. If the weight of gases is increased the rate of heat impartation to the instrument is also increased. When more heat is put into the instrument than is radiated from it its temperature, T_1, rises. This rise in T_1 increases the rate of heat radiation from the instrument and decreases the rate of heat impartation to it. The rise in T_1 continues until the two sides of the equation are equal. Therefore the higher the velocity of the gases the smaller is the temperature difference $T-T_1$ on the left side of the equation and the smaller the radiation error.

RELATION OF HEAT RADIATING AND RECEIVING SURFACES OF INSTRUMENT.

The extent of the surfaces S and S_1 is the most important factor in measuring temperatures of moving gases inside of a boiler setting. It is the only factor that can be controlled in the temperature measurements under any given conditions of boiler operation, the weight of the gases w then remaining constant.

The extent of the surface, S, receiving heat by convection is always greater than the radiating surface, S_1. This fact follows from the nature of the modes of heat transmission to the instrument and from it. Convection delivers heat not to the surface of the metal or glass of the instrument, but to the gaseous film surrounding the solid surface. The thickness of this gas film is probably the same no matter what the diameter of the instrument, so that it can be said that the extent of the heat-receiving surface S is roughly proportional to the quantity $d+2\delta$, where d is the diameter of the instrument and δ is the average thickness of the gas film.

To make this reasoning logical, it is necessary to state that the amount of heat imparted by convection is proportional to the difference between the temperature of the hot moving gas and that of the surface of the gas film. That is, if T_3 is the average temperature of the surface of the gas film, the rate of heat convection is equal to $C(T-T_3)$, because in our consideration of the size of the instrument w the weight of gases remains constant and is embodied in C. But under these conditions $(T-T_3)$ is proportional to $(T-T_1)$ and therefore $C(T-T_1)$ can be used in place of $(T-T_3)$.

This proportion is evident, and can be shown in the following way. The same quantity of heat $C'(T-T_3)$, imparted to the gas film by convection, must be transmitted through the gas film by conduction and may be expressed by the formula $C''(T_3-T_1)$, where C'' is a constant. We can therefore write the equation—

$$C'(T-T_3)=C''(T_3-T_1)$$

or

$$K(T-T_3)=(T_3-T_1).$$

By definition of temperatures

$$T-T_1=(T-T_3)+(T_3-T_1)=(T-T_3)+K(T-T_3).$$

Therefore

$$(T-T_1)=C(T-T_3)$$

Inasmuch as the gases are permeable to radiation and when heated themselves radiate practically no heat, the extent of the heat-radiating surface of the instrument is the same as that of the metal or glass of the instrument. It can be said, therefore, that S_1 is proportional to the diameter d of the instrument. It is evident that when the diameter d decreases S_1 decreases faster than S, and therefore the amount of heat radiated from the instrument decreases faster than the heat imparted to it by convection. As a result of this unequal decrease the temperature of the instrument rises when its diameter decreases. This feature can be made clearer by the following specific example:

In the experiments reported in this bulletin two thermocouples were used to measure the temperature of the gases inside the boiler setting. One of these couples was about 0.500 inch in diameter and the other was 0.008 inch. If the thickness of the film is assumed to be 0.010 inch, the heat-receiving surface, S, of the large couple is

$$S \propto (0.500+0.02)$$

and the heat-radiating surface of the same couple is

$$S_1 \propto (0.500).$$

The heat-receiving surface of the small couple is

$$S \propto (0.008+0.02)$$

and the heat-radiating surface of the same couple is

$$S_1 \propto (0.008).$$

By stepping from the large couple to the small couple the heat received has been diminished by the quantity $\frac{0.520}{0.028}=18.5$, whereas the heat given off has been reduced by the quantity $\frac{0.500}{0.008}=62.5$.

The reduction of the surface controlling the heat given off is 3.4 times larger than the reduction in the surface controlling the heat received. As a result of these unequal reductions of surfaces, the temperature difference between the instrument and the boiler tube (T_1-T_2) must be increased and the difference between the temperature of the gas and that of the instrument decreased in order that the equality between the two heats is maintained, and consequently the temperature indicated by the smaller couple is much nearer to the temperature of the moving gases than that indicated by the large couple.

The unequal decrease in the heat-receiving and the heat-radiating surface when the diameter of the couple is decreased is illustrated in figure 18. It is strikingly apparent that in the upper diagram illustrating a cross section of a large couple, the ratio of the surface of gas film to the surface of the instrument is much smaller than it is in the lower diagram illustrating a cross section of a small couple.

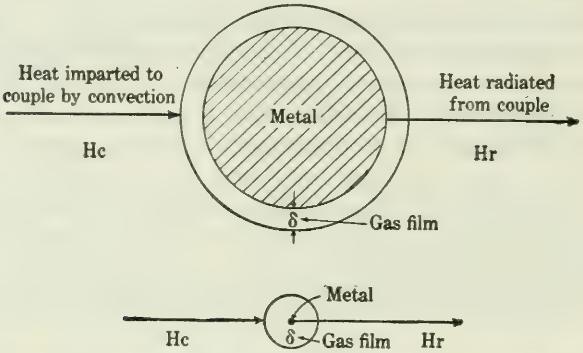
Heat imparted to couple by convection
Hc
Metal
Heat radiated from couple
Hr
δ
Gas film
Metal
Hc
δ
Gas film
Hr

FIGURE 18.—Diagram showing that the surface radiating heat decreases faster than the surface receiving heat by convection, when the diameter of the instrument decreases. Hc, heat imparted by convection to couple. Hr, heat radiated from couple.

EXPERIMENTAL DATA SHOWING RELATION BETWEEN SIZE OF THERMOCOUPLE AND RADIATION ERROR.

It has been shown in the preceding pages that in measuring the temperature of the gases in a boiler setting the radiation error was much smaller with the small couples than with the large ones. Therefore it is safe to assume that with any given conditions of exposure of the couples the radiation error has a definite relation to the size of the couple. To establish such relation for the conditions similar to those met with in the temperature measurements described in this bulletin two sets of four couples of different sizes were made and their temperature indications when placed in a boiler setting were studied. One of these sets was of platinum and platinum-rhodium and the other of copper and constantan. The diameters of the copper-constantan couples were 0.550, 0.250, 0.024, and 0.008 inch, and those of the platinum couples were 0.450, 0.310, 0.024, and 0.008

inch. Of these couples the two small ones of each set were made similar to the small couples of the respective sets shown in figure 11, and the construction of the two large couples of each set was similar to that of the large couples shown in the same figure. The four couples of each set were clamped together in such a way that the hot junctions were about 1 inch apart; the two large couples were on the outside and the two small ones on the inside of the group. The platinum and platinum-rhodium set was placed in position *A* of the double-pass Heine boiler, where it was partly exposed to the boiler tubes. The copper-constantan set was placed in the hood, or position *F*, of the same boiler. At the beginning of the experiment the 0.024-inch couple of this set broke, so that readings with only three couples were obtained. Readings of all these couples were taken in rapid succession, and while the readings were being taken the furnace conditions were kept as uniform as possible. Smokeless Pocahontas coal was used to avoid as much as possible the deposition of soot and other solids on the couples.

RELATION BETWEEN DIAMETER OF COUPLE AND INDICATED TEMPERATURE.

The results of four series of readings obtained with these couples are plotted in figure 19. The two sets of curves *A* and *B* at the top of the figure show two series of readings taken with the platinum and platinum-rhodium couples, and the sets of curves *C* and *D* at the bottom of the figure show two series of readings taken with the copper-constantan couples. In each group the order of the curves is according to the size of the couple, the lowest curve representing the readings obtained with the largest couple and the highest curve the readings taken with the smallest couple.

Plotting the diameter of the couples as abscissas and the readings of the couples as ordinates gave the curves shown in figure 20. The highest curve *A* in this figure contains four points representing the averages of three series of readings obtained with the four different sizes of couples when placed in position *A* in the double-pass Heine boiler (see fig. 6). In this position the couples were exposed largely to the walls and the bottom of the furnace, partly to the tile roof, and to a small extent to the tubes of the boiler, so that the exposure to the hot brick surfaces greatly predominates. This brickwork was heated to dull red or to about 700° C.

The curve *B* contains four single readings taken under the same conditions of exposure as *A*, but with somewhat lower temperature of the surrounding surfaces and of the gases.

The curve *M* contains two average points taken with a twin couple placed in position *B* in the Babcock & Wilcox boiler shown in figure 2. In this position the couples were exposed almost entirely to the surfaces of the boiler tubes, which were at a temperature of about 275° C.

The curve *N* passes through three points, which are the averages of several readings taken with three sizes of couples placed in the uptake of the double-pass Heine boiler in the position indicated by *F* in figure 6. At this place the couples were partly exposed to the surfaces of the boiler, the surfaces of the brick uptake, and the surfaces of the sheet-metal hood. The average temperature of these surfaces was probably close to 210° C.

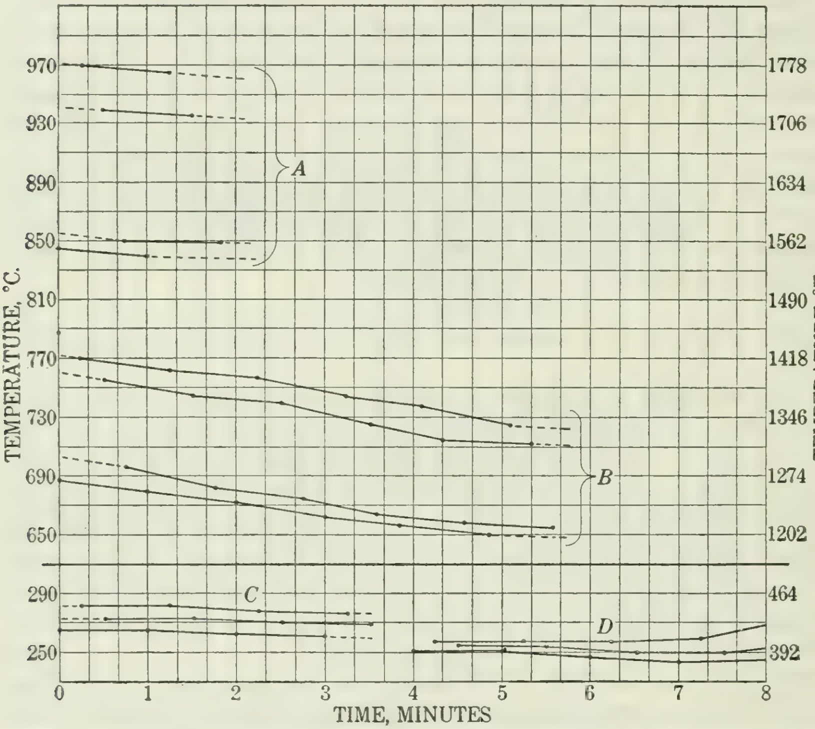

FIGURE 19.—Curves showing temperature indicated by couples of different sizes when placed in same position in a boiler setting. Series *A* and *B* were taken with four platinum and platinum-rhodium couples, 0.008, 0.024, 0.310, and 0.450 inch in diameter placed in position *A*, figure 6. Series *C* and *D* were taken with three copper-constantan couples, 0.008, 0.250, and 0.550 inch in diameter, placed in position *F*, figure 6. In each group the order of the curves is according to the size of the couple, the smallest couple reading the highest and the largest one the lowest.

Strictly speaking, the readings of the two largest platinum couples are not comparable with those of the two smallest couples, because the radiating surface of the large couples was fused silica, which has a larger coefficient of emissivity than the platinum of the two small exposed couples. But the effect of the difference of emissivity of the two materials is comparatively small and can be neglected so far as the purpose of this bulletin is concerned.

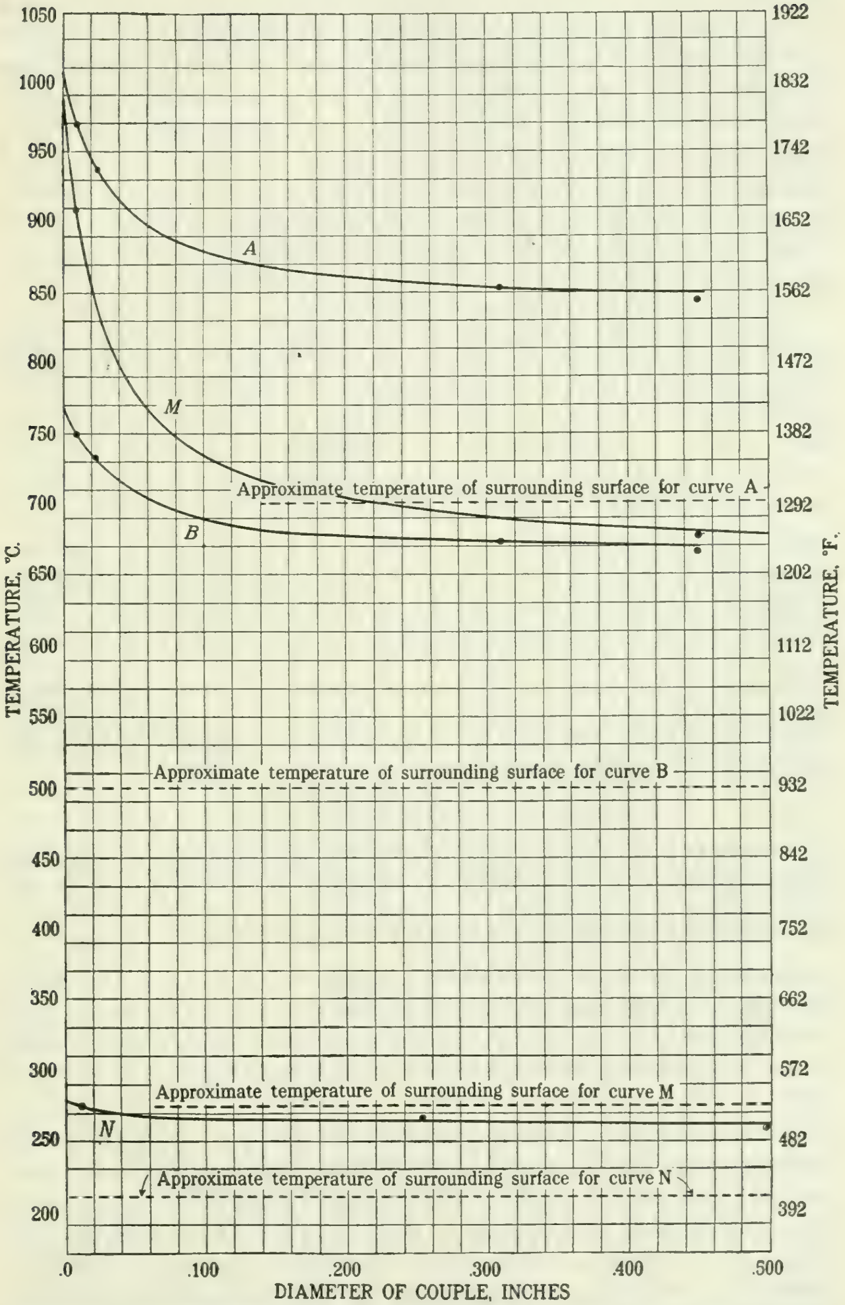

FIGURE 20.—Curves showing relation between diameter of couple and temperature indicated by couple, when measuring temperature of hot gases surrounded by cooler surfaces. Temperature for zero diameter of couple is true temperature of gases.

The curves in figure 20 show that as the diameter of the couple decreases the radiation error decreases very slowly at first, and then rapidly as the couple is reduced through the very small sizes to zero diameter. The correct temperature of hot gases flowing through a passage surrounded by colder surfaces can be obtained only with a couple of zero diameter, the construction of which is a physical impossibility. Therefore under the given conditions the correct temperature of the gases can be closely approximated by the use of curves such as are shown in figure 20. The smaller the couple the nearer will it indicate the true temperature of the gases.

The relation between the radiation error and the diameter of the couple is not a simple one because of the many factors entering in, such as the temperature of the gases, the temperature of the surrounding colder surfaces, and the amount of exposure to these surfaces, but can be approximated by using equation 3 (see p. 35). On account of the temperature variable being expressed as the fourth power, the equation is rather cumbersome, and its solution can be made much easier by making T_2 equal to 1 and expressing the other temperatures as ratios of T_2, remembering what this provisional unit is and changing the final results into the standard units. Such substitution of units eliminates one fourth-power factor and reduces the value of the constant $\frac{C}{K}$ to a convenient figure. Substituting arbitrary temperature units by this method, the equation of the two curves A and B takes the form,

$$D[(T_1)^4-(T_2)^4]=3.9(D+0.08)(T-T_1).$$

For the curves M and N, which represent conditions of exposure and velocities of gases different from those of curves A and B, the values of the constant $\frac{C}{K}$ are 12 and 10.8, respectively.

According to these equations the thickness of the gas film about the couple is 0.04 inch or about 1 millimeter. This value may seem too large, but with smaller values the part of the curve near the zero diameter end would rise more rapidly than the observed points permit.

It is also probable that the thickness of the gas film varies with the temperature and somewhat with the diameter. It would seem that as the diameter of the couple becomes smaller its temperature rises, and because of this rise in temperature and the reduction in diameter the thickness of the film decreases. However, if such a decreasing value for the thickness of the gas film is substituted, the left end of the curve rises too rapidly and misses the points representing temperatures obtained with the small couples.

Data at hand are not complete enough to justify a more detailed theoretical investigation of the thickness of the film and other constants in the equation. The discussion given in the preceding paragraphs has been presented as a suggestion of a possible method by which the radiation error problem can be solved. For the satisfactory solution of the problem a far more complete set of observations is necessary. Such data will have to be obtained in a specially designed apparatus where all the conditions can be controlled; a boiler setting is not in that class of apparatus. The data presented in this paper show beyond doubt that when the temperature of moving gases surrounded by colder surfaces is measured by couples of different diameters, the temperature indicated by the couples forms a curve which has a very steep bend as the diameter of the couple approaches zero. The smaller the couple the nearer does it indicate the true temperature of the gases.

EFFECT OF TEMPERATURE OF GASES ON RADIATION ERROR.

From the discussion of equation 3 (see page 35) and the curves of figure 20, it is apparent that the higher the temperature of the gases in any given gas passage, the higher is the radiation error, and the greater will be the difference between the temperature readings of two couples having different diameters. This feature is shown more clearly by the curves in figure 21, which were compiled from the temperature measurements plotted in figures 1, 3, 5, 7, and 9. In this figure the differences between the temperatures indicated by the small and the large couple are plotted as ordinates and the temperature indicated by the small couple as absicssas.

Figure 21 shows the temperature differences for the Babcock & Wilcox, the Parker, the Stirling, and the two Heine boilers. The readings for each of the five boilers are indicated by differently shaped points, and the readings of each twin couple are represented by a group of points inclosed by an irregular line, the position of the couple being designated as shown in figures 2, 4, 6, 8, and 10. All the points fall close to some line that passes through the point representing zero ° C. and 32° F., and rises as the temperature rises. These lines show a slight curvature with the convex side toward the abscissas, indicating that the difference increases faster than in direct proportion to the temperatures.

EFFECTS OF CONDITIONS OF EXPOSURE OF COUPLE ON RADIATION ERROR.

Figure 21 shows also that the radiation error is different for different conditions of exposure of the couples. Thus all of the twin couples placed among the boiler tubes of the Babcock & Wilcox boiler had the same conditions of exposure, and therefore the points representing their readings fall along one smooth curve. The twin couple *A*, however, was partly exposed to the boiler tubes and partly to the furnace walls, which were hotter than the tubes, and therefore its radiation error was less. This is shown clearly by the fact that the points representing readings of this twin couple fall on a curve considerably below the curves for the other couples. Thus, for example, when the small couple of the twin *B* read 900° C., the large couple read 230° C. lower; when the small couple of the twin *A* read 1,100° C., the large couple read only about 160° C. lower than the small one. This feature has been discussed in connection with equation *3* on page 35.

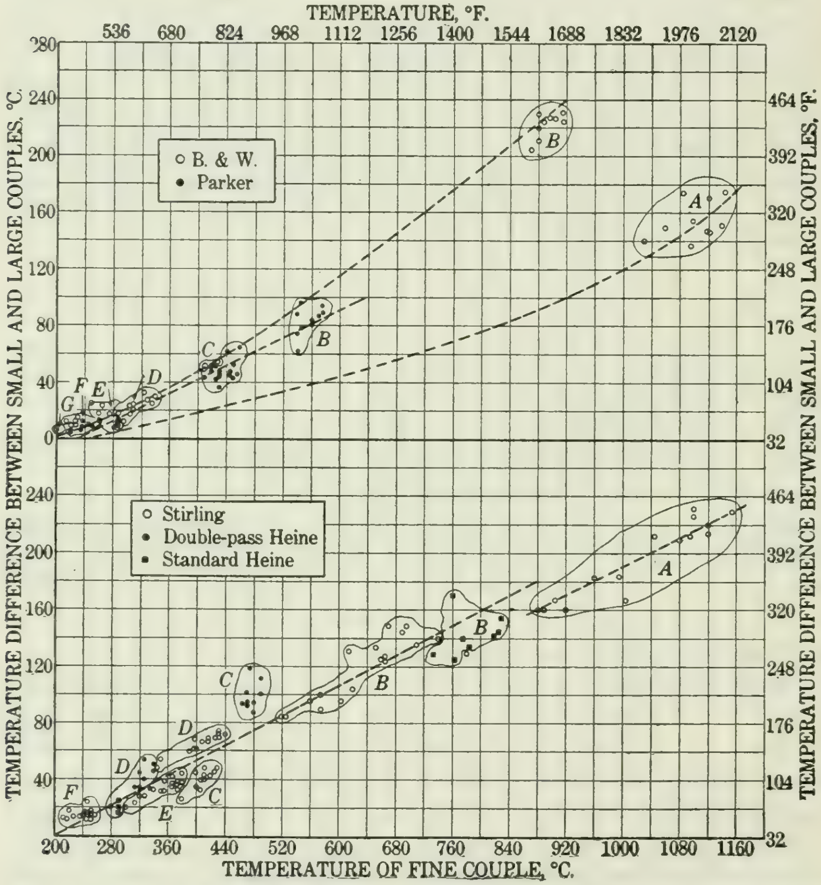

FIGURE 21.—Curves showing effect of temperature of gases on radiation error. Results of temperature measurements in five types of boilers. Measurements by each twin couple are represented by a group of points inclosed within a thin border line and are designated by the position of the couple.

CONCEPTION OF THE GAS FILM NEXT TO SURFACES OF SOLIDS.

The conception of the reality of the gas film around a solid is a fundamental factor in the explanation of the fact that the radiation error is smaller with small couples than it is with large ones. The layer or film of gas at the surface of a solid body is not a mathematical factor but is a physical reality, although rather difficult to define exactly. It is perhaps easier to describe such a film than to define it. The following is the authors' conception of the film:

Figure 22 will help in making this conception clear. When a solid body *A* is placed in a stream of moving gas, a very thin layer of gas adheres to its surface and has no motion. This layer of immovable gas is perhaps only two or three gas molecules thick, and is probably similar to the layer of water adhering to the surface of a solid when it is wetted by dipping in water. Next this layer of immovable gas is another layer which moves, but its velocity is very small compared to the average velocity of the gas stream. Farther away are successive layers, each of which has a velocity somewhat greater than the preceding one, until the velocity of the main body of the stream of gases is reached. The rate of increase in velocity of the successive layers is at first small, but becomes greater and

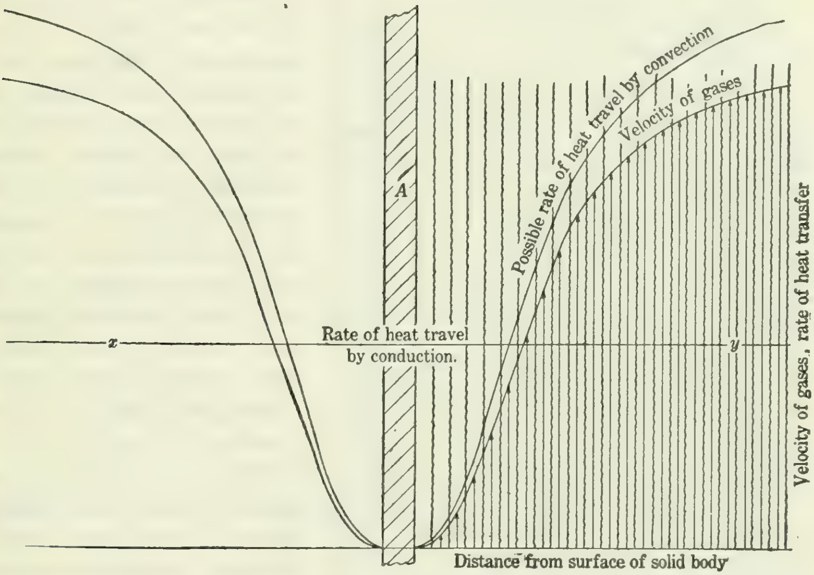
A
x
y
Rate of heat travel by conduction.
Possible rate of heat travel by convection
Velocity of gases
Velocity of gases, rate of heat transfer
Distance from surface of solid body

FIGURE 22.—Diagram showing the relative velocity of infinitesimal layers in a film of gas next to a solid surface. Layers are represented by spaces between wavy lines; velocities of layers by length of arrows. Curve having ordinates proportional to velocity represents possible rate of travel of heat by convection; horizontal line *XY* represents possible rate by conduction. A plane parallel to *A* and passing through point of intersection of the two curves may be considered the surface of the gas film.

greater until the layers about one-eighth of an inch from the solid body are reached; then the rate again becomes smaller as the layers having maximum velocity are approached. In figure 22 the successive layers of gas are represented highly magnified by the spaces between the wavy lines, and the magnitude of their motion is indicated by the length of the arrows. Thin, wavy lines are used to indicate that the successive layers are not sharply separated but merge into one another. The particles of gas, in fact, pass from one layer into another by the rolling motion of small eddy currents. The spaces representing the layers are shown very wide in order to make the diagram clear. In reality the thickness of each layer is infinitesimal, so that the entire width of the diagram on one side of the solid *A* represents the conditions in a space of about one-eighth of an inch thick, measured from the surface of the body. The smooth curve connecting the heads of the arrows indicates the variation in the velocity of the gases within this small space. The curve is shown to have a double curvature, being convex near the surface of the solid body, and concave farther away near the layers having the average velocity of gas stream. The curvature near the surface of the solid extends through only a very short distance from the surface, and is practically impossible to show experimentally.

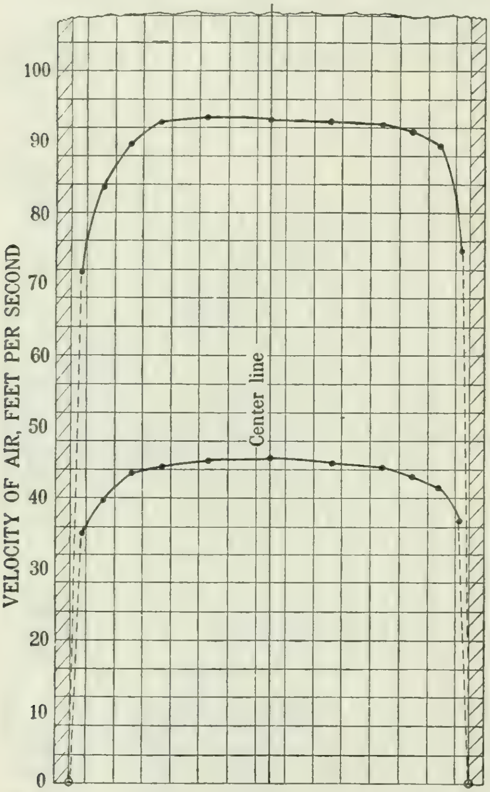

FIGURE 23.—Diagram showing variation in velocity of air current across diameter of an 8-inch pipe as actually measured with a small Pitot tube.

The great change of velocity within a space of one-eighth of an inch of the surface of a solid is represented in figure 23, which shows the velocity of an air current at different points in the cross section of an 8-inch pipe, as actually measured with a small Pitot tube. Two sets of measurements of two different rates of flow are given. With the higher rate of flow, the velocity drop from the center of the pipe to one-eighth of an inch from the surface of the pipe is 22 feet per second. The drop within a $\frac{1}{8}$-inch layer at the surface of the pipe is 71 feet. Drops of similar proportions were shown with the lower rate of flow.

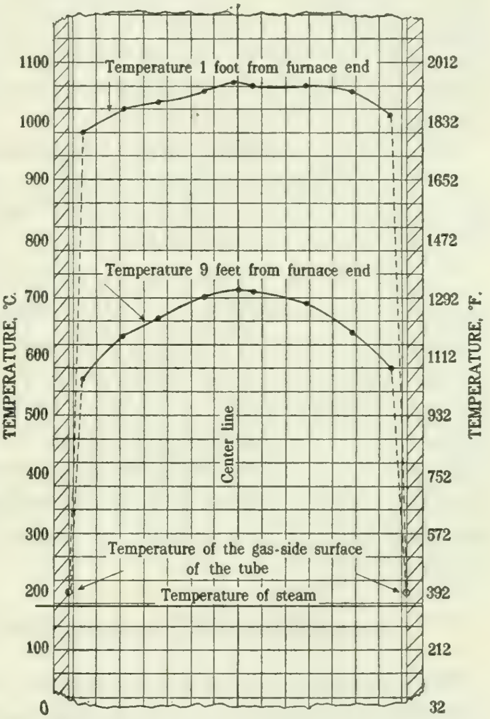

FIG. 24.—Diagram showing variations in temperature of gases across a boiler tube $2\frac{3}{4}$ inches in internal diameter. Temperatures were measured with an exposed platinum couple at 9 points on a vertical diameter. Upper curve represents temperature 1 foot from furnace end, average velocity of gases 108 feet per second; lower curve represents temperature 9 feet from furnace end, average velocity of gases 78 feet per second. Compare these temperature curves with the velocity curves of figure 23.

When hot gases flow through a boiler tube the variation of temperature of the gases across a section of the tube is similar to the variation of velocity. This fact is shown in figure 24, which gives two sets of temperature measurements across a vertical diameter in a tube of a horizontal tubular boiler. The tube was $2\frac{3}{4}$ inches in inside diameter and 20 feet long. The cross section at which the higher temperature was measured was 1 foot and that at which the lower temperature was measured was 9 feet from the furnace end of the tube. The temperatures were obtained with an exposed platinum and platinum-rhodium couple 0.012 inch in diameter. These two temperature curves indicate that by far the greater part of the temperature drop occurs within one-eighth of an inch distance from the walls of the tube, where the velocity drop occurs. The largest temperature drop is in the layer of gases next to the surface of the solid, where there is no motion at all or only a comparatively small one. Farther toward the center of the tube where the velocity is high, the temperature drop is small. Inasmuch as the temperature drop along a path of heat travel to a great extent indicates the resistance flow of heat these layers of inert or slow-moving gas present the highest resistance to the passage of heat, and the cause of the high resistance is obviously the lack of motion. With a given quantity of heat to transmit to the boiler tube, there must either be high velocity or high temperature drop along the path of heat travel; when the velocity decreases the temperature drop must increase in about the same proportion. In other words, there must be either a high velocity of the gases to transmit the heat by convection, or a large temperature drop to transmit it by conduction.

It has been sufficiently proved that the rate of heat travel through gas by convection is very nearly proportional to the velocity of the gas; and also that within reasonable limits of temperature the rate of heat travel by conduction is nearly constant. Therefore a curve such as the curving line in figure 22 can be drawn, its ordinates being made so proportional to the velocities that they represent the rate of heat travel by convection. The rate of heat travel by conduction, being constant, can be represented by a horizontal line, such as x y in the figure. Above the point of intersection of the two curves, convection is the predominant mode of heat travel, whereas below the intersection point conduction predominates. The layers of gas near the surface of the solid body, where conduction predominates, are considered by the authors as the gas film and are represented in figure 18 by δ.

MEASURING THE TEMPERATURE OF FLUE GASES.

The steam-boiler operator frequently has need of determining accurately the temperature of the gases leaving the boiler. He may be confronted with the question of what is a good way of measuring flue-gas temperatures.

INSTRUMENTS USED.

Two types of instruments are in general use for measuring the temperature of flue gases—mercury thermometers and thermocouples. The mercury thermometers specially designed for this purpose are about 3 feet long and have a temperature range up to 1,000° F., and are usually placed in a protecting steel tube $\frac{1}{2}$ to $\frac{3}{4}$ of an inch in diameter. Unprotected thermometers about 18 inches long and of somewhat smaller temperature range are also used. The advantages of using thermometers are that the temperature can be read directly, and their low first cost. The chief disadvantages are that they have a large radiation error and, owing to their limited length, can not be placed at the most favorable point in the stream of gases, which introduces another considerable chance for error. Another unfavorable feature is that frequently they have to be placed at an inaccessible part of the uptake or flue, so that reading is inconvenient. Breakage and destruction from flames in the flue adds considerably to the cost of using them.

The thermocouples used in measuring flue-gas temperatures are made of either platinum and platinum-rhodium or of different kinds of base metals. Among the base metals the ones most frequently used are the Hoskin couple, made of nickel and nickel-chrome alloy, iron and constantan, and copper and constantan. Couples of various forms made of these metals can be bought in the market ready for use. Each of these couples has its advantages and disadvantages. The platinum couple has the advantage that the metal does not contaminate easily and, therefore, does not require recalibration, even with long usage. Its disadvantage in measuring flue-gas temperatures is that it has a low electromotive force, necessitating the use of a delicate galvanometer to indicate the temperature. The high cost of the couple, and of the galvanometer, is also a serious drawback to its use. The base-metal thermocouples have an electromotive force about four times that of the platinum couple and, therefore, small changes in temperature are easily measured with greater accuracy. They are more easily contaminated, and for that reason require more frequent testing. However, their first cost is so low that they can be frequently renewed without making their use expensive. The necessity of using an indicating instrument and its inherent weaknesses are a serious drawback in the use of all couples, whether of platinum or of base metal.

The galvanometer, which is the instrument most frequently used with a couple to indicate the temperature, measures the potential drop across its binding posts and not the potential impressed by the couple. If the internal resistance of the galvanometer is very high as compared to the resistance of the couple and of the leads, the potential drop across the binding posts of the galvanometer is very near the potential impressed by the thermocouple. If, however, the internal resistance of the galvanometer is low and the resistance of the couple and its leads is high and variable a serious error is sure to enter into the temperature measurements. Therefore it is advisable to use a galvanometer with as high internal resistance as possible. High resistance galvanometers are necessarily delicate and therefore require careful handling when carried from place to place and must be carefully leveled and adjusted before readings are taken. Such galvanometers also cost considerably more than those having a low resistance.

A portable potentiometer, which obviates most of the objections to a galvanometer except the high first cost, measures the potential impressed by the couple no matter how long the leads are and how variable their resistance; it is accurate and does not easily get out of order. Also a potentiometer is compact and robust in construction; it can be easily carried around a steam plant and does not need careful leveling for accurate reading.

During more than 12 years of testing work in commercial plants, as well as with special experimental apparatus, the writers tried various combinations of the instruments mentioned in the preceding paragraphs. They obtained the most satisfactory results with the copper-constantan thermocouple used with a portable potentiometer. Therefore detailed directions are given herein for using this combination in measuring flue-gas temperatures.

MAKING A COPPER-CONSTANTAN THERMOCOUPLE.

PURCHASING THE ELEMENTS.

Owing to the possibility of a couple being contaminated and the low cost of the copper-constantan thermocouple elements, it is advisable to buy the two kinds of wire in lots of several hundred feet and make couples of suitable length as they are needed. Whenever there is a suspicion that a part of the couple is contaminated this part can be cut off, or an entirely new couple made. Renewal of the couple is justified by the low cost. Five dollars will buy about 1,000 feet of each wire of No. 22 (B. & S. gage). When bought from a reliable maker any one roll of the wire is of very uniform composition, so that for practical purposes one calibration can be depended on for all of the wire in the roll. The writers, in testing the wire they use, found that calibrations of thermocouples made from various parts of a given roll checked very closely. No. 22 (B. & S. gage) wire is about 0.024 inch in diameter and a couple made from it has sufficient mechanical strength, also the wire is small enough so that the radiation error when the couple is inserted in the uptake is small. When buying the wires it should be specified that they are to be used for thermocouples, giving the thermoelectric relation about as shown by the curve in figure 28. This curve has been obtained by repeated calibration of couples made from the same rolls of wires in the physical laboratory of the Bureau of Mines.

MAKING THE HOT JUNCTION.

The hot junction can be made by welding the ends of the two wires together in a gas blowpipe or a gasoline blowtorch, borax being used as a flux. It is rather difficult to bring the wires to welding temperature with an ordinary Bunsen gas burner. The writers obtained very good results with a gasoline blowtorch, which is available to practically all steam-plant operators. The following procedure will give good results:

Cut off the desired length of each wire and roll the two wires in separate coils 2 to 3 inches in diameter, leaving about 4 inches of each wire uncoiled. Get the blowtorch burning so that it gives a steady hot flame. Heat the free ends of the two coils to a red heat and quickly dip them while hot into powdered borax. The borax will adhere to the wires and form a coating which protects them from oxidation. Stand close to the torch with the flame blowing directly away; then, holding one of the coils in each hand, insert the borax-coated ends of the wires into the flame about 1 inch from the nozzle of the torch.

The elbows should be held against the body to give steadiness and the ends of the wires should be placed in the upper or lower edge of the cross section of the flame. Holding the wires near the edge of the flame insures rapid heating of a short length of the wire, the center of the flame not being as hot as the edges. The copper wire comes to melting point first. When both of the wires are at the point of fusion press the two ends together, then, holding the arms rigid, by slightly moving the body remove the junction from the flame and hold until cold. Holding the arms rigid prevents the junction being pulled apart while hot. A little practice may be necessary before a satisfactory joint is obtained. After the manipulation is once learned a good junction can be made at the first trial. However, if success does not come after repeated trials the welding can be accomplished by first fusing a very small piece of copper wire over the end of the constantan wire and then welding the copper wire to the coppered end of the constantan wire. After a good weld has been made the junction may be trimmed with a file so that it is of the same thickness as the rest of the wire.

MAKING THE BODY OF THE COUPLE.

After a satisfactory junction has been formed and is properly trimmed the wires of the couple are insulated with small glass tubes and placed in a $\frac{1}{4}$-inch or $\frac{3}{8}$-inch standard iron pipe of suitable length. To prevent the glass tubes from slipping out of the iron pipe, pieces of asbestos rope can be packed tightly around them at each end of the pipe. The hot-junction end of the couple can be made to project about 1 inch from the glass tubing, the latter being either flush with the end of the iron pipe or projecting about a half of an inch from it.

The cold end of the pipe can be fitted with a simple handle containing two binding posts to which are connected the free ends of the couple. The construction of this simple couple is shown in figure 25. An iron pipe 5 or 6 feet long will answer all the requirements for measuring the temperature of flue gases in an ordinary boiler plant. The thermocouple wires may be cut 3 or 4 feet longer than the pipe and the extra length can be wound around the binding post. Whenever a piece of the hot end of the couple is cut off on account of contamination enough wire can be unwound from the binding posts to make up for the part cut off.

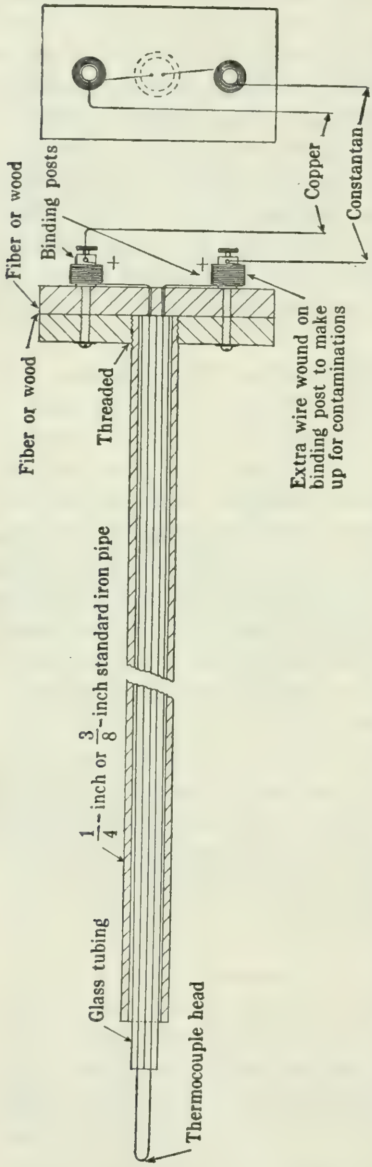
Fiber or wood
Binding posts
Copper
Constantan
+
+
Extra wire wound on binding post to make up for contaminations
Fiber or wood
Threaded
$\frac{1}{4}$-inch or $\frac{3}{8}$-inch standard iron pipe
Glass tubing
Thermocouple head

FIGURE 25.—Diagram showing construction of body of copper-constantan couple for measuring flue-gas temperatures.

ARRANGEMENT OF THE COUPLE, ITS COLD JUNCTION, AND THE INDICATOR.

For rough measurements of flue-gas temperatures the indicating instrument can be connected with copper leads to the binding posts of the thermocouple. The cold junction of the couple is formed in the binding post where the copper lead joins the constantan element of the couple. The approximate temperature of the cold junction can be obtained by hanging a low-reading thermometer either on the binding post or near it so that the thermometer indicates nearly the temperature of the binding post. This temperature must be taken into consideration when figuring the temperature indicated by the couple. This type of cold junction is simple, and for that reason it is frequently used in couples for measuring the temperature of flue gases. It has the drawback that its temperature can not be determined accurately and that the observer must climb on top of the boiler to read it.

The temperature of a water-bath cold junction attached to the couple as shown in figure 11 can be obtained quite accurately, but its location is not convenient for reading in everyday boiler-room work.

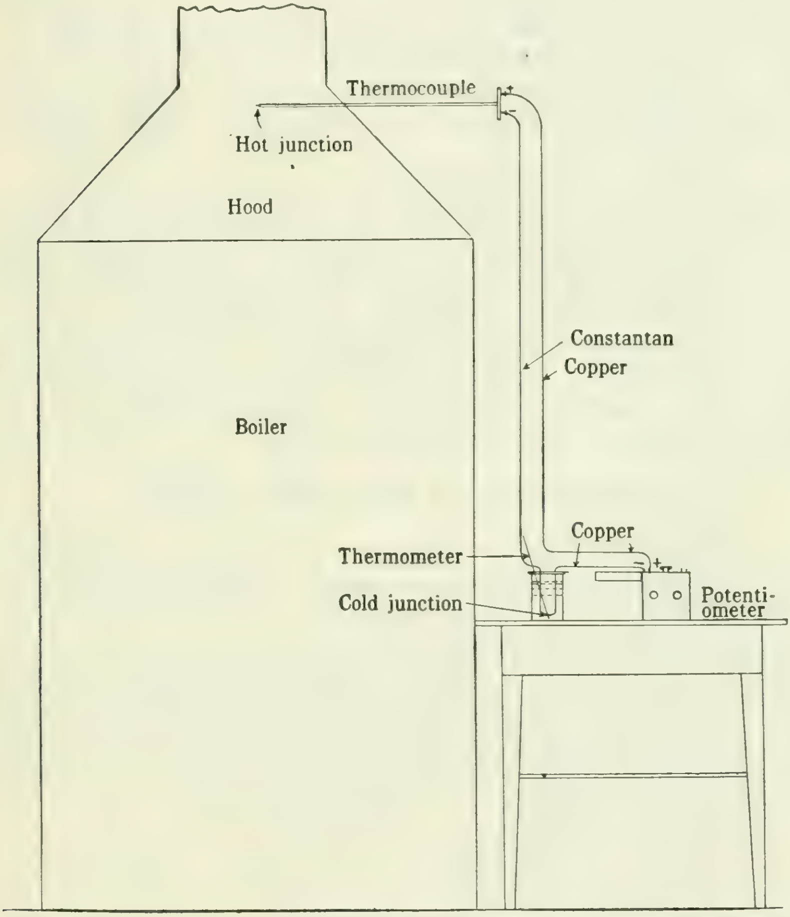

FIGURE 26.—Diagram showing arrangement of thermocouple, its cold junction, and the indicating instrument, when measuring the temperature of flue gases.

Perhaps the most satisfactory arrangement is the one in which the cold junction is placed with the indicating instrument on a table or a bench standing on the floor of the boiler room as shown in figure 26. An insulated copper wire is lead from the copper terminal of the couple directly to the positive binding post of the potentiometer. From the constantan terminal of the couple a constantan wire leads down to a water bath. To the lower end of the constantan lead is soldered a piece of copper wire about 18 inches long, and the soldered junction is placed in the bend of a glass **U** tube which is submerged in a vessel of water as shown in figure 26. The free end of the piece of copper wire is connected to the negative binding post of the potentiometer. The cold junction of the couple is the soldered joint between the constantan wire and the short piece of copper wire placed in the bend of the **U** tube. Its temperature is determined by a thermometer inserted in the water bath, the temperature of the junction being the same as that of the water bath. This arrangement is very convenient to read and gives accurate results. The operator can read the potentiometer and the cold junction at the same time.

For most of the boiler-room testing work the water bath at the cold junction can be omitted and the constantan lead can be connected directly to the negative binding post of the potentiometer, the binding post of the instrument then being the cold junction. Its temperature can be fairly closely obtained by laying a thermometer over the instrument. The temperature of the binding post usually does not vary greatly, and the thermometer can be read from time to time when the potentiometer is read. This arrangement is a simple one and gives very satisfactory results.

MANIPULATION OF THE POTENTIOMETER.

An explanation of the principle of a potentiometer, and descriptions of the different types and makes of such instruments are omitted here because the reader can obtain such information in any textbook on laboratory physics and in the catalogues of different makers. The writers use in their work a small portable Leads & Northrup instrument mounted in a wooden box about 10 inches long by 6 inches wide by 6 inches high and weighing about 10 pounds. The manipulation of this instrument is herein described; other types and makes are manipulated in the same general way.

ADJUSTING THE INSTRUMENT.

Figure 27 gives the top view of the instrument connected for reading. An ordinary dry cell battery, connected as shown, is used, the standard cell inside the instrument being used only to standardize the dry cell. The first thing to be done after connecting the various parts of the apparatus is to see that the pointer of the galvanometer points to zero. If it does not, it must be adjusted by slightly turning the screw *D* in the direction that the pointer should be moved. This must be done very carefully, as a very slight motion of the screw changes the position of the pointer considerably.

After this adjustment has been made, the dry cell must be standardized. This is done by pressing the key *Sc* and turning the knob *R* one way or the other until the pointer of the galvanometer points approximately to zero. The final accurate adjustment is then done by turning the knob *F*, which requires considerable motion to move the pointer through a very small angle. When the pointer is properly adjusted and the dry cell standardized, the pointer should have no perceptible motion when the key *Sc* is alternately pressed and

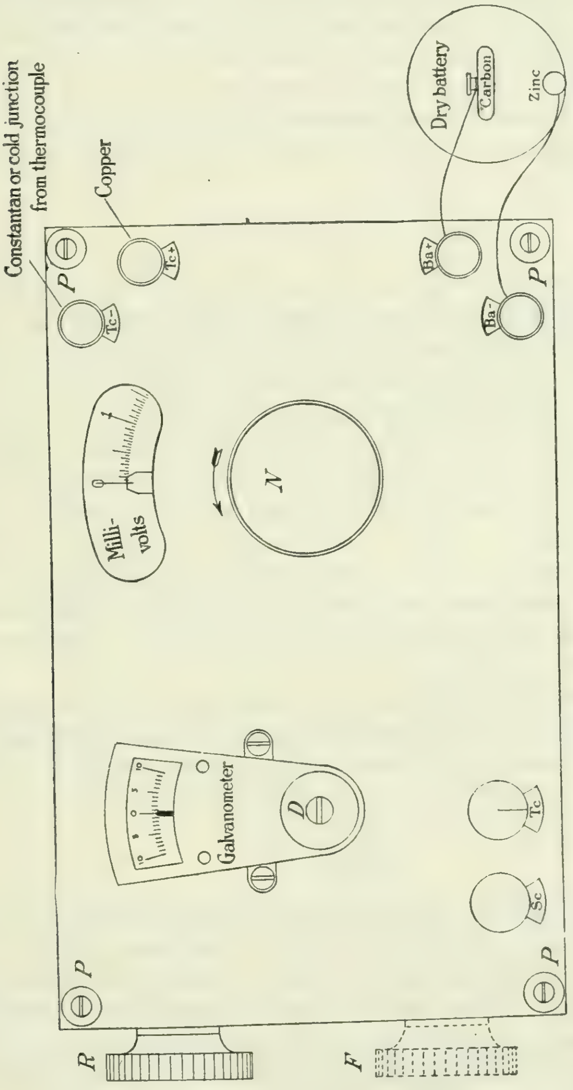

FIGURE 27.—Top view of a portable potentiometer. *D*, Screw for initial adjustment of galvanometer pointer; *R*, knob of coarse resistance for standardizing dry cell; *F*, knob of fine resistance for standardizing dry cell; *N*, knob for reading potential of couple; *Sc*, button to be pressed when standardizing dry cell; *Tc*, button to be pressed when reading potential of couple; *Ba* −, negative binding post of battery; *Ba* +, positive binding post of battery.

released, and should stand at the zero point of the small scale of the galvanometer. The instrument is then ready for temperature readings. As the voltage of the dry cell changes somewhat with constant use, the adjustment should be frequently checked by pressing the key *Sc.* It may seem that the adjustment of the instrument and the standardization of the dry cell is a difficult and tedious task, but with a little experience the former takes about a minute, and the latter only a few seconds. Usually one adjustment a day of the pointer is sufficient unless the instrument is moved to different places, in which event the adjustment should be checked each time the instrument is moved.

READING THE TEMPERATURES.

Before reading the temperature the operator should make sure that the thermocouple leads are properly connected to the instrument. The constantan lead should be connected to the negative binding post and the copper lead to the positive post. To read the temperature the key *Tc* is depressed and the knob *N* turned in the direction indicated by the arrow until the galvanometer pointer is brought to the zero point of the small galvanometer scale. The reading is obtained from the scale turned with the knob *N*, and is given in millivolts.

The millivolt reading can be converted into temperature by means of a calibration curve such as shown in figure 28. The following is a general method which takes into account also the temperature of the cold junction:

Obtain the number of millivolts corresponding to the temperature of the cold junction; add this to the number of millivolts obtained from the potentiometer. The temperature corresponding to the sum is the temperature of the gases as measured by the couple.

EXAMPLES.

The following specific example illustrates the method: Suppose the reading of the potentiometer is 16.25 millivolts and the temperature of the cold junction is 20° C. Starting from the point representing 20° C., at the left of figure 28, follow the horizontal line until it intersects the curve; from this point follow the vertical line to the scale at the bottom and read the corresponding millivolts, which is 0.80. This, the cold junction correction, should be added to the number 16.25 read from the instrument, giving the sum 17.05 millivolts. On the scale at the bottom of the diagram estimate the position of the point 17.05, and from it follow an imaginary vertical line to the curve; from the intersection point of this imaginary line and the curve follow an imaginary horizontal line to the centigrade scale at the left or the Fahrenheit at the right. The temperature is 340° C. or 644° F.

Another example is as follows: The temperature of the cold junction is 35° C., and the potentiometer indicates 17.50 millivolts. The correction of the cold junction, corresponding to 35° C. as obtained from the curve, is 1.3 millivolts. Adding this to the reading of the potentiometer gives 1.3 plus 17.50 equals 18.8 millivolts. The temperature corresponding to this value is 370° C. or 698° F.

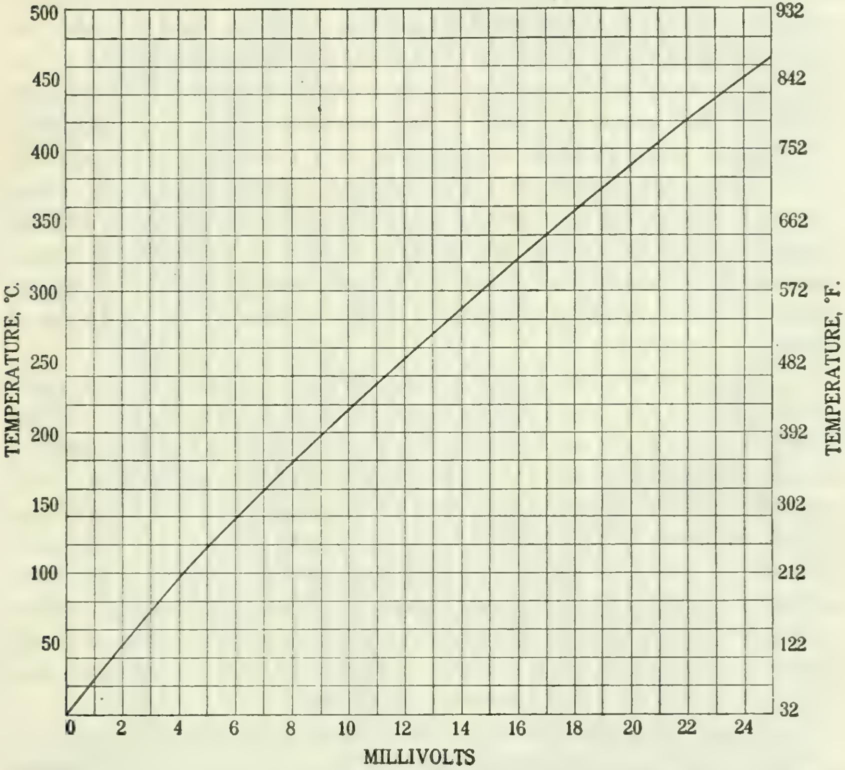

FIGURE 28.—Curve showing relation between millivolts and temperature for a copper-constantan couple.

PLACING A THERMOCOUPLE FOR MEASURING FLUE-GAS TEMPERATURES.

In measuring the temperature of flue gases, the position of the thermocouple is very important. Although no specific directions can be given as to the exact point for placing the thermocouple, it can be said that in general it is best to insert the thermocouple into the hood or uptake in such a way that the hot junction is in the center of the stream of gases and as far as possible from any cold surface. Before any definite position is selected the hot junction of the thermocouple should be moved to different points in the stream of gases and the difference in temperature noted. The couple can even be moved and inserted into different holes in the uptake or breeching. After this preliminary survey of the temperatures at different points the operator can decide for himself the best position for the couple. It is perhaps generally the best to place the couple where it gives the highest temperature, otherwise the results are apt to be affected by air filtering in or by radiation to some cold surface to which it is exposed. The radiation error, however, is far less in a couple constructed as directed on page 51 than it would be if a thermometer were used. It is highly improbable that the indicated temperature will be too high. An excellent example of a high radiation error when a large flue-gas thermometer was improperly placed is given by the tests made on a Stirling boiler at the Williston plant of the United States Reclamation Service, described in Bulletin 23[a] of the Bureau of Mines.

Figure 29 shows the boiler setting and the position of two thermometers used for measuring temperatures of the flue gases. In the figure the small circles between the rear wall and the last nest of tubes are horizontal coils for preheating air used in combustion. The top half of these coils receives cold air directly from the blower and the temperature of the tubes was perhaps 100 to 150° F. The temperature of the rear drum was probably 325° F., which is the temperature of steam at 125 pounds gage pressure, the pressure carried by the boiler. The bulb of the lower thermometer was about 1 foot from the preheating coils, midway between the rear steam drum and the wall and about 3 feet below the damper.

The upper thermometer was placed about 4 feet above the damper in the hood of the stack, which extended over the uptake of another boiler, forming one battery with the test boiler. During the testing this other boiler was banked and the flue gases, which were at a very low temperature, entered the same stack as the gases from the test boiler. There was no partition separating the two halves of the hood, so that the cool gases from the banked boiler could partly mix with those from the test boiler, thereby lowering their temperature. Furthermore, the sheet-iron hood always radiated a considerable quantity of heat and was, therefore, colder than the gases on the inside. Consequently the thermometer bulb in the hood lost some heat by radiation to the sheet-iron hood and was at a lower temperature than the gases passing it. Nevertheless the thermometer in the hood indicated a temperature considerably higher than that indicated by the thermometer below the damper. The thermometers were exchanged several times, but their indication persistently bore the same relation as regards position, no matter what thermometer was used. The table following shows the temperatures as obtained by the two thermometers.

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[a] Breckenridge, L. P., Kreisinger, Henry, and Ray, W. T., Steaming tests of coal and related investigations, 1912, pp. 306–8.

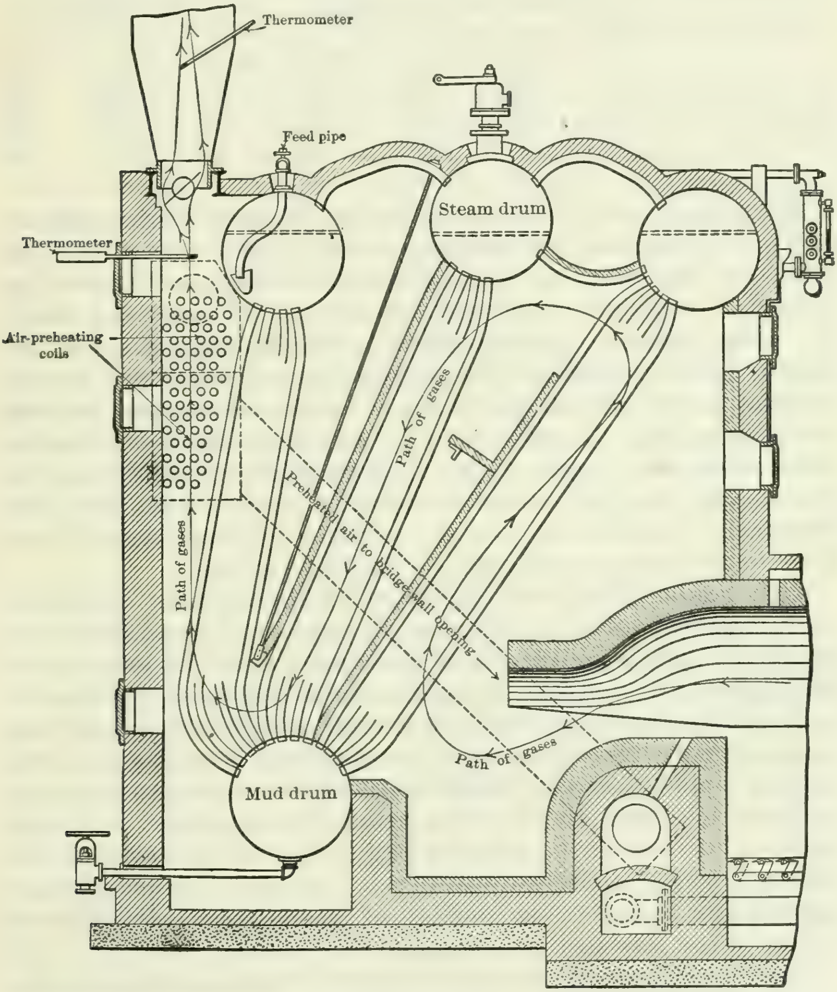

FIGURE 29.—Setting of a Stirling boiler at plant of U. S. Reclamation Service, Williston, N. Dak. Shows position of two thermometers used for measuring temperature of flue gases.

Flue-gas temperatures obtained at two places in a boiler setting.

Test No.	Reading of thermometer above damper.			Reading of thermometer below damper.		
	Average.	Maximum.	Minimum.	Average.	Maximum.	Minimum.
	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*
1	442	450	435	374	400	335
2	470	500	435	373	410	350
3	559	624	320	457	510	360
4	436	470	385	379	425	325
5	473	520	420	418	460	355
6	519	555	465	448	475	400

Often great care is taken to calibrate a flue-gas thermometer to within 1 degree, and then the instrument is placed carelessly in the uptake of the boiler setting and correct results are expected or claimed without any attention being paid to the disturbing effects of cooling surfaces. A thermometer placed in the sun would not indicate the temperature of the surrounding air, nor would a thermometer placed between two pieces of ice in a warm room indicate the temperature in the room, but some operators, when measuring the temperature of a stream of gas inside a boiler setting assume the thermometer reading to be absolutely correct because the thermometer is known to be correctly calibrated, without regard being given to the temperature of the surrounding surfaces.

After reading the preceding discussion the operator will better appreciate the importance of proper placing of a thermocouple when he desires to obtain fairly reliable measurements of the temperature of flue gases. Inasmuch as copper-constantan couples are inexpensive and easy to make he may even find it worth while to use two or three couples put in different places of the uptake of breeching and read them in rapid succession. In this event all the constantan wires can be joined together into one cold junction, and the copper wires can be led to a two or three pointed switch. With this arrangement the different couples can be read within a few seconds. Similar arrangement can be used for any number of couples placed in different boilers to compare their performance.

The radiation error practically always exists and as a rule averages about 20° F. (See figs. 1, 20, 21, and 22.)

USEFULNESS OF TEMPERATURE MEASUREMENTS.

When the instruments for measuring the temperature of gases have once been procured, and the operator has learned to use them, he can obtain with them much useful information about the performance of the boilers. Besides, the plant may contain other apparatus in which the determination of temperature is desirable. The coper-constantan couple may be used for reading temperatures up to 1000° F.

In many boiler plants the temperatures of flue gases are measured only when evaporation tests are run. The temperature of the flue gas, together with its analysis, furnish information concerning the magnitude of heat losses in the waste gases. Inasmuch as this item of heat losses is the largest one in the boiler room, and is also one that can usually be considerably reduced, the temperature measurement is an important part of the test data.

In other tests the measurement of flue-gas temperatures may be found useful. Thus by determining the flue-gas temperature before and after blowing the soot off the heating surfaces of a boiler, the detrimental effect of the soot coat on the efficiency of the boiler can be determined. Approximately, the efficiency of the boiler as a heat absorber increases 1 per cent for every 25° F. drop in flue-gas temperature, provided the furnace temperature and the rate of combustion are constant. By studying the data thus obtained, the operator can determine the best length of time between successive blowings. If scale and mud deposits on the inside of the boiler, its effect can be also fairly closely determined by measuring the flue-gas temperatures before and after cleaning the boiler. In any one investigation, considerable data should be collected and the averages used, so as to eliminate the effect of variation of other conditions, before any definite conclusions are drawn.

CALIBRATION OF THERMOCOUPLE.

The simplest way of obtaining a calibration curve for the thermocouple is to buy wires having thermoelectric properties conforming to some standard curve like the one given in figure 28. Different pieces of wire from the same roll can be relied upon to vary not more than 3 to 4 degrees, which is probably within the allowable limits of error in measuring the temperature of flue gases, because of the radiation error and the variation in temperatures of different points in the same cross section of the gas stream.

The best calibration can be obtained by sending a thermocouple to the Bureau of Standards, Washington, D. C. The price of calibration is $7.50 per couple.[a] The unavoidable delay in getting such a calibration is a serious objection in many instances.

If the boiler-room operator possesses a reasonable amount of manipulative skill he can calibrate his own couples with fair results. He can use one of these two methods:

(*a*) Determining three or more temperature points of the couple with known melting points of some pure metals; and

(*b*) Comparing the thermocouple with a mercury thermometer of known calibration.

---

[a] Prices for calibration of various instruments are given by "Pyrometer testing and heating measurements," Bureau of Standards, Circular No. 7, 1913, 17 pp. This circular can be obtained by writing to the Director of the Bureau of Standards.

CALIBRATION BY KNOWN MELTING POINTS OF METALS AND BOILING POINT OF WATER.

Three metals, zinc, cadmium, and tin, are well suited for this purpose, and their melting points are:

Zinc	melting point	420° C.	787° F.
Cadmium	do	321° C.	610° F.
Tin	do	232° C.	450° F.

A fourth point can be obtained with the boiling point of water, which is 100° C. (212° F.).

PREPARING THE MOLTEN BATH.

The melting points given for these metals are those of Kahlbaum's pure metals, which may be difficult to obtain. Chemically pure metals can be purchased from any reliable chemical supply house. These are not absolutely pure, and their melting points are 2 to 5° C. lower than those given for Kahlbaum's pure metals. Therefore, if the chemically pure metals are used, a deduction of about 4° C. should be made from the melting points given above. About two pounds of each metal should be purchased, which will suffice for many calibrations.

These metals can be melted in iron crucibles heated with two gasoline blowtorches. The crucible should be surrounded with fire brick, magnesia blocks, or some other heat insulating material to prevent rapid dissipation of heat; otherwise, it might not be possible to obtain temperatures high enough to melt zinc and cadmium. Suitable crucibles for this purpose can be made of pieces of standard 1-inch iron pipe 8 inches long and closed at one end with caps as shown in figure 29. It is advisable to make separate crucibles for each metal, and to keep the metal in its crucible after calibration is completed. The use of separate crucibles will tend to prevent possible contamination of the metals and avoid the difficulties that will surely be encountered in taking the metals out of the crucibles and putting them in again when needed in future test work. All contamination should be carefully guarded against, as the melting points of the metals would be lowered, and serious errors might result. As a matter of fact, the metals are contaminated to a slight degree by being heated in the iron crucibles for a long period. However, from the experience of the authors this contamination lowers the melting points less than 1° C.

PRECAUTIONS IN MAKING READINGS.

When heating the metal the exposed surface should be covered with graphite or powdered charcoal to prevent rapid oxidation. The depth of the molten metal bath should be 4 to 5 inches before the couple is inserted. When the couple is inserted the metal will rise to about 6 inches. The bare couple should never be immersed directly in the molten metal, but should be protected with a hard glass or a fused silica tube closed at one end. These protective tubes should be about ½ inch in outside diameter and 10 inches long, the walls being about one-sixteenth of an inch thick. Fused silica tubes can be obtained from any firm supplying scientific materials. The arrangement of the thermocouples when placed in the bath of molten metal is shown in figure 30.

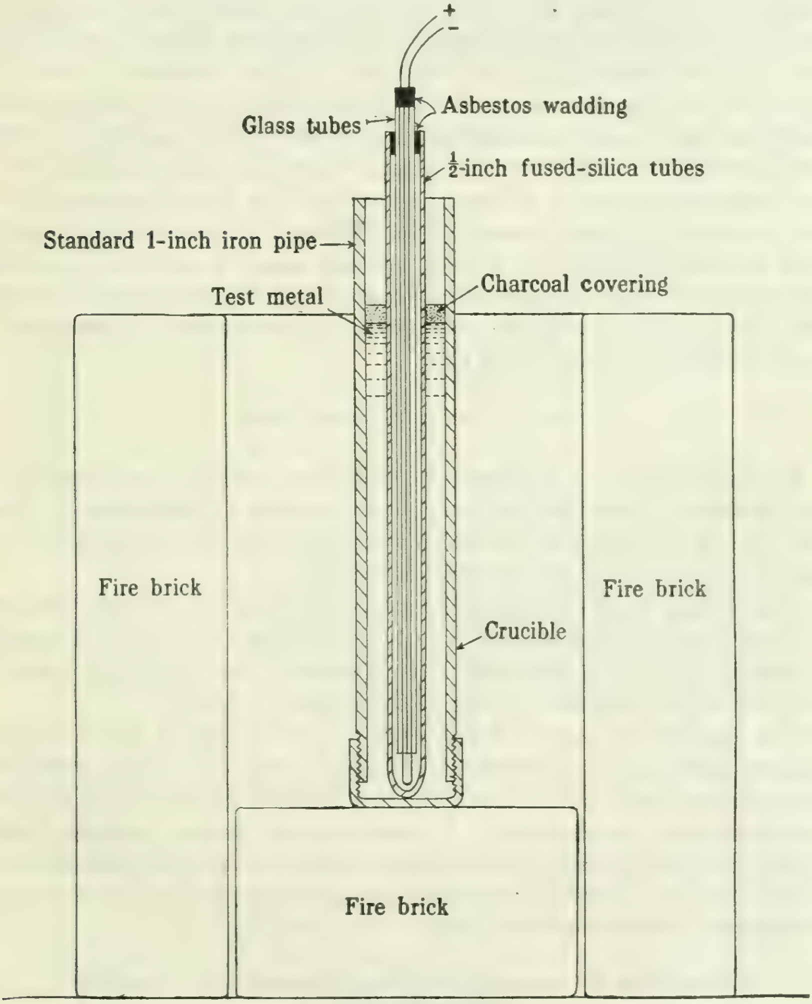

FIGURE 30.—Arrangement of apparatus for calibrating thermocouple by known melting points of metals. The crucible is surrounded with fire brick to prevent dissipation of heat from the crucible.

When calibrating the couple the cold junction should be placed in an ice bath if possible, which will avoid complicated corrections in making the calibration curve. The metal should first be melted and then heated about 30° C. above its melting point. Then the couple, protected by the silica tube, should be inserted the full depth of the metal bath. The blowtorches should then be removed, and while the metal is cooling off readings should be taken every 10 seconds until the metal has solidified, which takes 5 to 10 minutes. The readings will show at first a marked drop in temperature, but when the metal begins to solidify the temperature will remain constant for a number of readings. After the metal has solidified there will again be a uniform drop in temperature. The constant temperature readings are the melting point of the metal. If the operator wishes to check his results, he can apply the blowtorches to the crucible and take readings while the temperature is rising. The temperature will continue to rise until the metal begins to melt, then remain constant for several readings. When the melting has been completed the temperature will again start to rise. When the operator is satisfied that he has obtained the correct melting point he should take the thermocouple and the protecting tube out of the metal bath before the latter solidifies too hard, otherwise the contraction of the metal is apt to crack the protecting tube.

PLOTTING THE CALIBRATION CURVE.

If the temperature readings are plotted as ordinates and the time as abscissas a curve like the one shown in figure 31 is obtained. The flat part of the curve is the melting temperature of the metal and is one of the points for the calibration curve.

The boiling point of water is easy to determine. The thermocouple is placed unprotected in a bath of boiling water to a depth of about 8 inches. With a given barometric pressure the temperature indication remains constant as long as the water is boiling.

The calibration curve of the couple is obtained by plotting the known melting temperatures of the metals and the boiling point of water as ordinates, and the corresponding millivolts obtained by the determinations as abscissas. A smooth curve drawn through these points gives the relation between the millivolts and the temperature of the couple. After a little experience four points on a curve can be obtained in three or four hours.

CALIBRATION BY COMPARISON WITH HIGH-READING MERCURY THERMOMETER.

If a good high-reading mercury thermometer is available a copper-constantan thermocouple can be calibrated by comparison with the thermometer. The two instruments can be immersed in a hot oil bath and read simultaneously. The oil used for this purpose should have a high boiling point so that it is possible to obtain temperatures of 600° or 650° F. Gas-engine cylinder oil is well adapted for such calibration. The oil can be heated in a vessel made of a piece of 4-inch iron pipe about 16 inches long and closed at one end with a cap. The heating should be done with a fire that can be easily controlled. A portable forge is well suited for this purpose. The vessel must be securely suspended over the fire so that there is no danger of its tipping over. The forge should be placed where the smoke would not be objectionable. The oil always contains some lighter constituents which should be boiled off before the instruments are immersed in the oil bath; otherwise the operator exposes himself to inconvenience from frothing and flaming of the oil, and to the danger of breaking the thermometer. The vessel is filled to a depth of about 12 inches with the oil and slowly heated. As the temperature rises the lighter constituents of the oil evaporate and the oil froths over and usually flashes up and burns. The operator need not be alarmed over this flaming. While the frothing continues the rate of heating should be reduced so as to give the light oil constituents time to boil off slowly. When the frothing stops the rate of heating can be again increased. The operator can ascertain approximately the

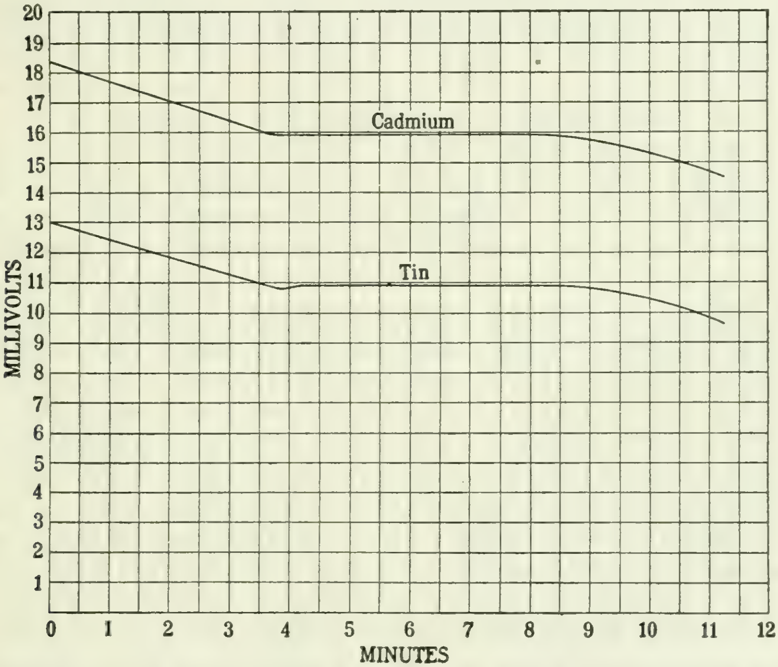

FIGURE 31.—Curves showing method of obtaining the melting point of a metal from a series of readings. The readings are taken while the temperature is falling.

temperature of the oil bath by dipping in the thermometer when each of the frothing spells subsides. If too much oil has been wasted during the frothing, it may be necessary to add more to keep the level of the oil within about 4 inches of the top of the vessel. Otherwise if the level is too low it is difficult to read the thermometer and at the same time have sufficient stem immersion.

After several of the frothing spells and perhaps additions of the oil the bath reaches a temperature of about 650° F. It is then ready for use for calibration, and the instruments to be compared are immersed. The thermometer and the couple are tied together in such a way that the bulb of the thermometer and the hot junction are close together; this helps to keep the two at the same temperature. They should be immersed in the oil to the greatest depth that will still permit the operator to read the thermometer. Between successive readings the bath should be thoroughly stirred to keep the oil of uniform temperature the entire depth. The two instruments should not be used as a stirrer; a flat iron rod can be used for this purpose. It is better to read the instruments while the temperature of the oil is constant or while it is slowly dropping, because under these conditions it is easier to keep the oil at the same temperature throughout the depth of the bath and the chances of the oil frothing over are avoided. Several readings of the two instruments should be taken in rapid succession, then the temperature of the oil bath can be allowed to drop 50 to 100° F. and another series of readings taken; thus in several such steps the whole range of the thermometer can be covered. During the reading of the high points the temperature is apt to change quickly, therefore it is advisable to have two observers, one reading the thermometer and the other the thermocouple. At the lower points the temperature changes slowly and one observer is able to read both instruments. During such calibrations the cold junction of the couple should be kept at the temperature of melting ice if possible. After the calibration is completed the oil should be preserved for future use, thus saving oneself the trouble of boiling out the light oils from a fresh supply of oil.

The calibration curve is obtained by plotting the temperatures of the thermometer as ordinates and the readings of the potentiometer in millivolts as abscissas.

The same apparatus and method can be used for comparing two thermometers.

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INDEX.

A. Page.

Air velocity in pipe, variations in, figure showing 46

B.

Babcock & Wilcox boiler, cross-section of, figure showing 13
- temperatures in, figure showing 12
- temperature variations in 25, 26

Boiler, horizontal tubular, temperature drop in 30
- *See also* boilers named.

Boiler temperatures, errors in obtaining, amount of 32
Boilers, used in test, dimensions of 11, 12

C.

Cadmium, melting point of 62
Calibration of thermocouples, directions for 61–66
Convection, heat transfer by, principles governing 36, 37
Copper-constantan thermocouple, construction of:
- figure showing 52
- diameters of 38

F.

Films, gas, on solids, conceptions of 45
- velocity of, figure showing 45

Flue-gas measurement, thermocouple arrangement for, figure showing 53
- temperature, measurement of, average errors in 9
  - instruments for 48–50
- radiation error in, example of 58, 59
- thermocouple for 57
- value of determining 61
- *See also* Gas.
- thermometer, radiation error in 58
- *See also* Gas, themometer thermocouple.

Forge, portable, use in thermocouple calibration 65

G.

Galvonometer, use of 49
Gas film, on solids, thickness of 42
- velocity of, figure showing 45
- on solids, conceptions of 45

Gases, boiler, temperature of, figure showing Page. 12, 14, 16
- *See also* Flue gas.

Gas temperature, effect of, on radiation error 43
- figure showing 43, 44

Gas temperature, measurement of, accuracy of, factors controlling 7
- measurement of, errors in 9

Gas temperatures in boiler tubes, variations in 25, 47
- variations in, figure showing 47

H.

Heat, convection of, principles governing 34
- radiation of, equations for 35
- transfer, factors governing 34–38
  - principles governing 34

Heine boiler, cross section of, figure showing 17
- gas temperatures in, figure showing 14
- temperature variations in 27, 28
  - figure showing 28, 29

Hot junction of thermocouple, welding of 50, 51

M.

Melting point temperature, determination of, figure showing 65
Melting points of metals, determination of 62
Muncey, E. M., acknowledgment to 8

P.

Parker boiler, cross section of, figure showing 19
- temperatures in, figure showing 18

Platinum thermocouple, advantage of 49
- construction of, figure showing 24
- description of 21
- diameters of 38

Potentiometer, connections of 54
- manipulation of 54, 57
- portable, figure showing 55
- reading of 56
- use of 50

R. Page.

Radiation error, effect of gas temperature on 44
  relation to gas temperature 43
  relation to thermocouple size 38, 42
  in temperature measurement 9
    causes 33
    example of 58
  See also Temperature measurements.

S.

Stirling boiler, cross-section of, figure showing 23, 59
  gas temperature variations in 27
    figure showing 27
  gas temperatures in, figure showing 22

T.

Temperatures, boiler, errors in, amount of 32
    fluctuations of 29
    variations in 26
  gas, measurement of, errors in 9
  See also Gas temperature.
Temperature drop in boiler 30
  amount of 32
Temperature reading, relation to thermocouple diameter 39
  relation to thermocouple size 39–43
    figure showing 40, 41
Temperature measurements, need of care in making 8
  radiation errors in, causes of 34, 37
    lessening of 24
    nature of 33
Temperature of boiler gases, figure showing 12, 14, 16
Thermocouples, arrangement of, for flue-gas measurement, figure showing 53
    base metal, advantages of 49

Thermocouples—Continued. Page.
  calibration from mercury thermometer 64–66
  calibration of, figure showing 63
    method of 61
  copper-constantan, construction of 52
  description of 20, 50
  diameters of 38
    relation of, to indicated temperature 39–42
  errors in reading of, sources of 9
  figure showing 24
  for flue-gas temperature, placing of 57
  impairment of, by use 25
  placing of, need of care in 60
  position of, figure showing 13, 14
  radiation and convection effects on, figure showing 38
  radiation error of 38
  size of, relation to indicated temperature 39–43
  size of, figure showing 40, 41
  unprotected, deterioration of 24
  welding of 50, 51
  wire for, selection of 50
  See also copper-constantan thermocouple, platinum thermocouples.
Thermometers for flue-gas measurements 48
  radiation error in 58
Tin, melting point of 62
Trinks, W., acknowledgment to 8

W.

Weidlein, J. P., acknowledgment to 8
Wire for thermocouple, selection of 50

Z.

Zinc, melting point of 62